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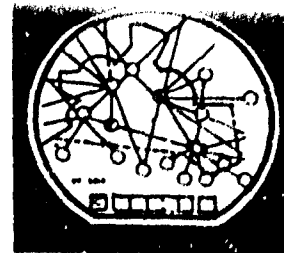


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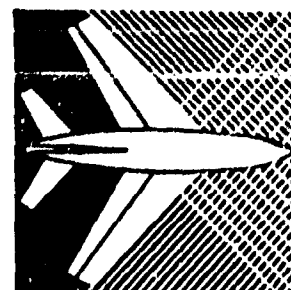
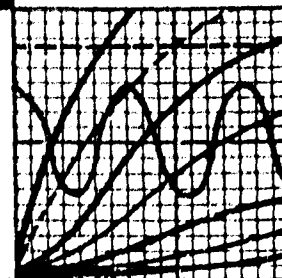
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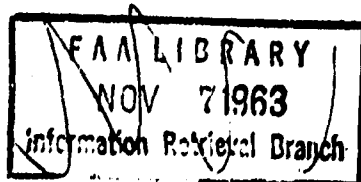
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Session I:
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ALL-WEATHER LANDING SYSTEMS



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CATEGORY II LANDING APPROACH SYSTEM FOR TURBOJET AIRCRAFT

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ABSTRACT

The International Civil Aviation Organization (ICAO) defines Category II Operational Performance as, "Operation down to minima below 60 metres (200 feet) and 800 metres (2600 feet) visibility and to as low as 30 metres (100 feet) and 400 metres (1300 feet) visibility with a high probability of approach success."

It is the purpose of this paper to define an airborne system for turbojet aircraft which will provide this capability. Emphasis will be placed on the selection of equipment and total system concept rather than on details of how the equipment operates. The selection of equipment is based on Douglas, industry, and Government experience.

Basically the components of a Category II system are common to all turbojet aircraft. Therefore, in this paper the recommended equipment for Category II operation with the Douglas DC-9 aircraft will be used as an example of a Category II system for turbojet aircraft.

CATEGORY II LANDING APPROACH SYSTEM FOR TURBOJET AIRCRAFT

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INTRODUCTION

The Douglas Aircraft Company believes that the basic components of an all-weather approach and landing system exist, and careful selection and integration of these components will yield a safe and reliable system at minimum cost. This approach, confirmed by experience gained during all-weather programs on the DC-8, is reflected in the DC-9 aircraft.

The basic design of the DC-9 and its systems will aid the operators in obtaining FAA approval to operate in weather minimums of 200 foot ceiling and 2600 foot visibility (ICAO Category I Operational Performance). Achieving ICAO Category II Operational Performance, 100 foot ceiling and 1300 foot visibility, is made possible through the introduction of add-on equipment which the basic aircraft and its systems are designed to accept.

The equipment required to operate to Category II weather minimums is predicated on the concept that, while deciding whether to land or initiate a go-around maneuver at the 100-foot commitment altitude, the pilot must be able to unhurriedly assess the approach situation and stay "on top" of the aircraft. When the aircraft arrives at this commitment altitude, it should be accurately aligned with the localizer and glide path beam centers, have the proper airspeed, and be stabilized so that the pilot can safely land the aircraft if he can see the runway from the 100-foot altitude or execute a go-around if the runway is not visible.

SYSTEM DESCRIPTION

Figure 1 illustrates the Category II low-approach system recommended for the Douglas DC-9 aircraft. The electronic components of the system are:

- Automatic pilot
- Automatic pilot monitor
- Flight director computer
- Flight instruments
- Instrument monitor
- Navigation receiver
- Vertical gyro
- Compass system
- Radar altimeter
- Vertical speed sensor
- Go-around computer
- Automatic throttle

The blocks in Figure 1 defined as "Air Data Computer" and "Stabilization" are components of the basic automatic pilot system. All of the equipment in the Category II system is dual with the exception of the automatic pilot and the automatic throttle control.

It can be seen from Figure 1 that there are three control paths (pilot, copilot, and automatic pilot) which may be used independently for control of the aircraft during the approach. Except that the three systems share some common components, triple redundancy is realized. How effective this degree of triple redundancy is depends upon:

- Reliability of the common components
- Prompt recognition of a failure or problem
- The pilots' ability to adequately fulfill their role in the control loop

The concept illustrated in Figure 1 eliminates the need for redundant automatic pilot and/or flight director systems and is compatible with the FAA philosophy presented in RFP 30R-3-1359 (All Weather Landing System For Turbo-Jet Aircraft). This FAA program will determine, among other things, the effectiveness of the manual instrument system in performing approaches and landings to the point of touchdown.

A "building block" principle is used to develop a safe and reliable Category II system at minimum cost for the

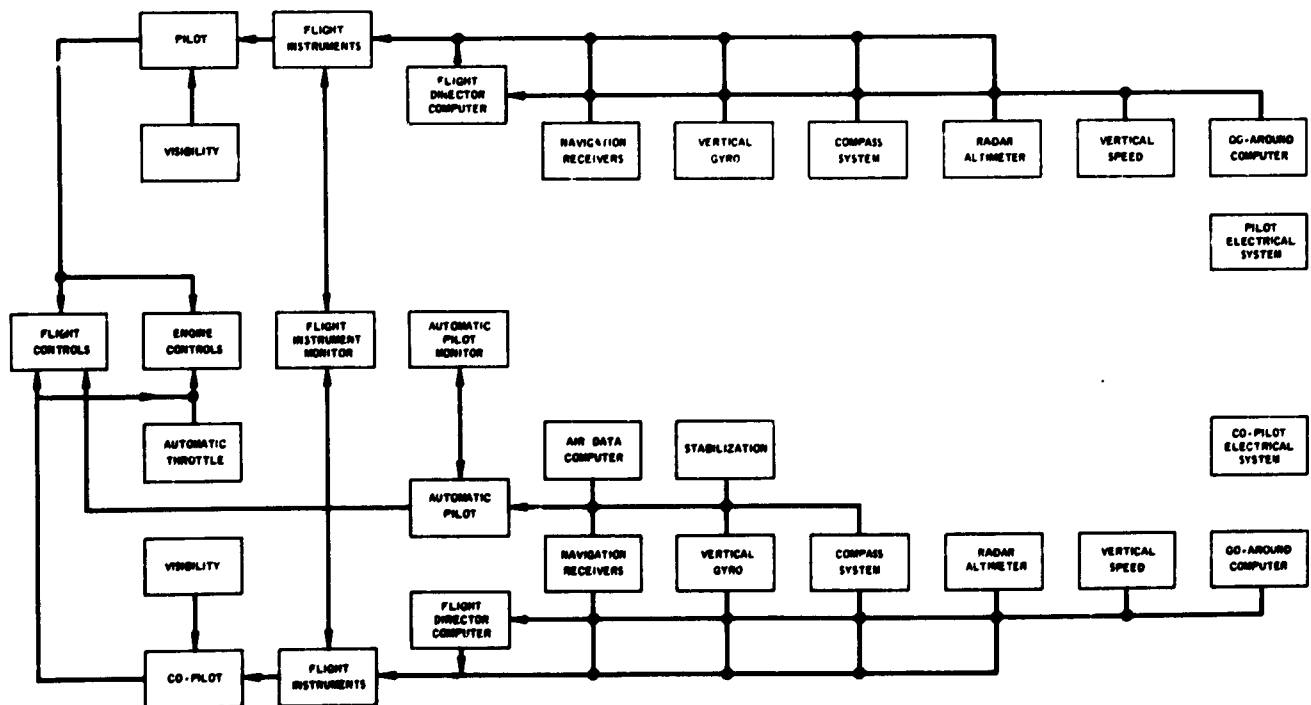


FIGURE 1. CATEGORY II LOW APPROACH SYSTEM FOR DC-9 AIRCRAFT

DC-9 aircraft. The basic DC-9 approach system provides Category I operation and the introduction of "add-on" equipment will provide Category II operation. This development sequence, which ultimately will yield a safe and reliable all-weather landing system, is based on the following:

- Elements added in each phase must not obsolete previously installed equipment.
- Existing fully developed airborne equipment is utilized where possible to reduce development costs and assure high reliability.
- The use of exotic equipment, either airborne or ground-based, is avoided.
- To aid in the reduction of equipment costs, maximum use is made of the pilot in monitoring the system and executing recommended procedures.
- The system enables the pilot and copilot to efficiently perform their tasks; thus, during the approach, the pilot can make prompt but unhurried decisions before any critical decision point is reached.

The basic DC-9 approach system, shown in Figure 2, provides the capability for ICAO Category I Operational Performance. The automatic pilot control coupled with an improved flight director and instrument display, improves the pilot's ability to monitor the approach, make decisions, and take over control of the aircraft at the breakout altitude. In addition, the improved flight director and display make it possible to perform accurate manual instrument approaches to low altitudes.

The minimum add-on equipment required to extend the approach capability of the DC-9 aircraft from Category I to Category II is shown in Figure 3. To further refine system performance, two additional items of equipment are recommended in addition to the minimum add-on equipment. This equipment, a second radar altimeter and an automatic throttle control, is circled in Figure 3.

Automatic Pilot

All of the essentials for providing automatic low-approach capabilities are embodied in the automatic pilot to be

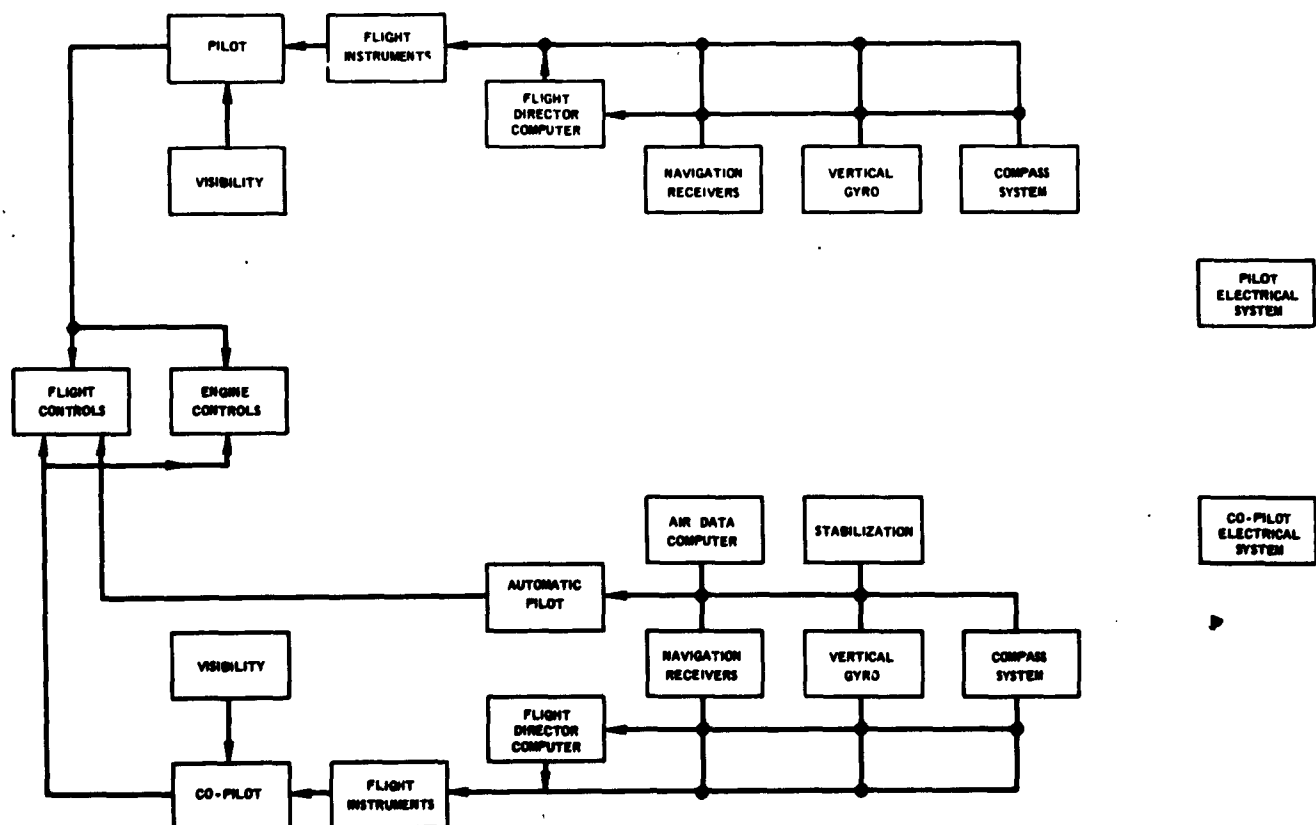


FIGURE 2. BASIC DC-9 APPROACH SYSTEM (CATEGORY I)

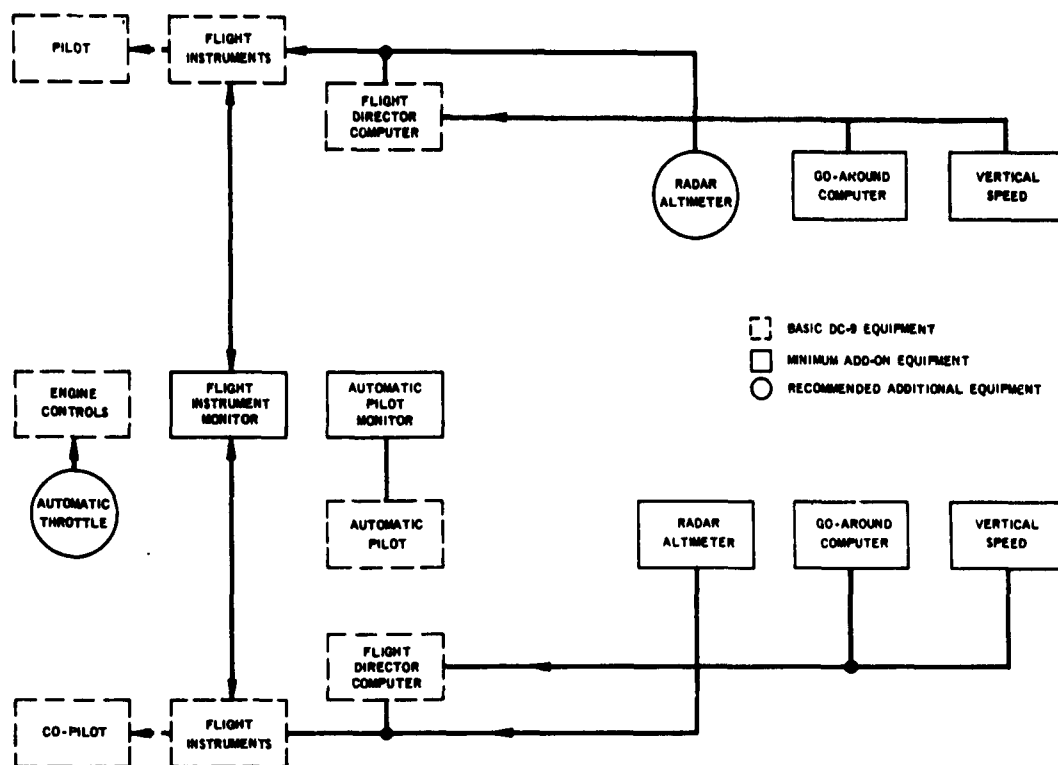


FIGURE 3. ADD-ON EQUIPMENT TO EXTEND DC-9 APPROACH CAPABILITY TO CATEGORY II

used on the DC-9 aircraft. Those features pertinent to the low approach (Category II) are:

- **Variable localizer intercept angle (0 to 90 degrees)**
- **Automatic ILS operation**
- **ILS gain programming**
- **Middle marker sensing**
- **Glide path extension**
- **Failure monitor**

Automatic ILS operation and the variable localizer intercept angle relieve the pilot of unnecessary action during an automatic approach. This allows him to focus his attention on assessment of the automatic pilot operation.

To achieve positive capture and accurate control on the ILS localizer and glide path beams during the initial phases of an automatic approach, high gains are necessary in the automatic-pilot radio-guidance circuitry. As the aircraft nears the approach end of the runway these high gains are detrimental to stable automatic pilot control, since the convergent characteristic of the localizer

and glide path beam causes the radio guidance gains to assume a higher than normal value. To compensate for the beam geometry, ILS gain-programming circuitry is provided in the DC-9 automatic pilot to linearly decrease the localizer and glide path control gains after interception of the glide path.

Another problem associated with the ILS beam, glide-path-beam distortion at low altitudes, has made necessary a requirement for some means of removing unflyable glide-path-beam information from a low approach system while maintaining the glide path angle to the flare initiation altitude. This requirement has been complied with in the DC-9 automatic pilot. When the aircraft flies over the middle marker beacon, a glide-path-extension mode based on memorized vertical speed is automatically initiated. In addition, a second stage of glide path gain programming is activated which linearly programs the glide path displacement gain from a low value to zero. By slowly fading out the remaining glide path beam information, a flight path reference is provided for an extended period without incurring a stability problem. If a middle marker beacon is not available at the airport, or is inoperative, the pilot can manually initiate the glide path extension mode at his discretion.

Automatic Pilot Monitor

To reduce pilot concern about automatic pilot malfunctions during the approach and assure safe operation at low altitudes, an automatic pilot failure monitor is included in the Category II system. This monitor detects active failures in the automatic pilot and automatically disconnects the servo system before any significant control surface deflection results. It is a fail-safe device, since failures in the monitor will also cause the automatic pilot to be disengaged. In addition, the contacts of the monitor relay are connected into the automatic-pilot-engage interlock circuitry so that the automatic pilot cannot be engaged if the monitor relay contacts fail in the open or closed position.

Flight Director System

The flight director system in the DC-9 aircraft provides a means for pilot assessment of the automatic approach, thereby allowing him to easily assume manual control of the aircraft if the automatic system malfunctions. It also provides the pilot with a means to perform an accurate manual instrument approach if he desires.

Compatibility with the automatic pilot is emphasized in a flight director system for low approach aircraft operation. The flight director system in the DC-9 aircraft achieves this through implementation of the following features:

- Variable localizer intercept angle (0 to 90 degrees)
- Automatic ILS operation
- Middle marker sensor
- ILS gain programming
- Glide path extension utilizing vertical speed

Emphasis has also been given to providing a natural, unambiguous display of information to the pilot on the attitude director indicator of the DC-9 to simplify interpretation and reduce "instrument searching." A three-dimensional design of the fixed aircraft symbol and the command bar displays the spatial situation of the aircraft during the approach and improves accuracy by reducing the parallax problem normally associated with pointer-type displays. ILS beam displacement information is provided by presenting glide slope deviation on the left side of the attitude director indicator and localizer deviation (in the form of a runway symbol) in the lower section of the indicator.

Instrument Monitor

An instrument monitor is added to the flight director system to monitor the critical navigation equipment. The monitor activates the pilot's and copilot's master warn-

ing lights on the glareshield and illuminates an equipment light on an annunciator panel. This informs the crew of any discrepancy in the navigation equipment so that they can readily take appropriate action. The inputs to the monitor system include:

- Compass system
- Pitch attitude
- Bank attitude
- Localizer receiver output
- Glide path receiver output

The localizer and glide path receivers were chosen as subsystems for the monitor system because a failure of either one represents a loss of reference to the desired approach flight path. Pitch attitude, bank attitude, and the compass system were selected because they are the basic references, providing stabilization about the three aircraft-control axes, for the pilot, instruments, and automatic systems.

The random location of malfunction warning and caution lights, which is detrimental to safe Category II operation, is eliminated by a master light and annunciator panel system in the DC-9 aircraft. Master caution and warning lights are located in the glareshield directly in front of both flight stations to ensure that they will be noticed immediately upon actuation. All annunciators are located in the forward end of the overhead panel. When a malfunction sensor is energized, the master lights at each flight station and the appropriate annunciator legend are illuminated. The pilot or copilot can scan the annunciator panel in a quick glance.

Go-Around Computer

The go-around maneuver becomes extremely important when operating down to 100-foot ceiling conditions. To ensure safety at low altitudes, a go-around computer is added to the Category II approach system. The go-around computer utilizes angle of attack and horizontal acceleration information to compute a safe and optimum go-around vertical steering command for the pilot's display. The pilot controls the aircraft pitch axis to keep the command bar of the attitude director indicator centered while thrust is applied and the aircraft is "cleaned up." This results in a minimum loss of altitude and in proper speed scheduling for optimum climb-out performance in the go-around maneuver.

The angle of attack transducer and horizontal accelerometer used for the go-around computation can also be used to compute an airspeed reference signal for display

to the pilot during an approach. By moving the throttles to satisfy the speed control indicator demands, the pilot can hold the airspeed necessary to maintain a given stall speed ratio for any aircraft weight, flap configuration, or g-maneuver. This speed control system can act as a monitor of automatic throttle control and provide a manual back-up for pilot control if the automatic throttle system malfunctions.

Radar Altimeter

A radar altimeter installation is provided in the Category II approach system to obtain precise altitude information above the runway so the pilot can accurately determine when the aircraft arrives at the 100-foot commitment altitude. This is essential to the pilot in his decision to land the aircraft or initiate a go-around maneuver. Barometric altimeters are not considered satisfactory for use at low altitudes because of lags in the system and the possibility of an inaccurate altimeter setting.

Unlike the other equipment in the Category II low approach system, which can be assessed in other phases of the flight envelope, the radar altimeter is not operational until shortly prior to its use in the critical period of the approach. For this reason, a self-test unit provides an in-flight check for pilot confidence.

Because height above the runway information is so critical for both the approach and go-around, a dual radar altimeter installation is recommended for a Category II low approach system.

Automatic Throttle

The Category II system described thus far is in general agreement with the thinking of all those concerned with all-weather operations. A possible exception may be the use of the dual radar altimeter installation. A second nebulous area is the use of automatic throttle.

Normally, aircraft speed control is accomplished by a proper blending of engine power, flap position, and pitch attitude by the pilot. Although adequate airspeed control can be accomplished in this manner, rigid cockpit procedures may increase the pilot workload and place him under pressure during an approach in adverse weather conditions. In addition, a manual or automatic approach can be degraded by too much throttle action and the aircraft may not be completely stabilized when the low approach minimum is reached. The addition of automatic throttle control is recommended for the Category II low approach system to substantially improve

the completed-approach/missed-approach ratio, thereby reducing the number of go-arounds. Automatic throttle control is especially beneficial when the pilot performs a manual instrument approach; he is relieved of the responsibility of manually controlling throttles to maintain airspeed and can devote his full attention to the attitude director indicator.

The airspeed reference signal computed from angle of attack and horizontal acceleration in the go-around computer can be used in the automatic throttle system. (It will be recalled that this signal is displayed on a speed control indicator for use by the pilot during manual control of airspeed in the approach.) Deviations from the computed airspeed reference are directed to a servo amplifier and servo drive which automatically positions the throttles to maintain airspeed.

In the DC-9 aircraft, the throttle servo drive is coupled to the throttle linkages through individual magnetic clutches (one for each engine) which must be energized for automatic throttle operation. Friction slip clutches are incorporated to enable the pilot to individually position each throttle lever without disengaging the system, and to provide a manual override capability.

Sensors

The remaining electronic components of the Category II system consist of the navigation receivers, vertical gyros, and the compass systems. These components perform their normal function of providing flight path and attitude references.

Electrical System

An additional feature of the DC-9 Category II system aids in satisfying the requirement that no single failure shall disable both the automatic system and the pilot's instrument system. This is accomplished not only by functionally isolating the systems but also by isolating their sources of power. The automatic pilot and the copilot's instruments and flight director system are connected to the same electrical bus; while the pilot's instruments and flight director system are connected to a separate electrical bus. This isolation also leads to a philosophy of system management which is well suited to the needs of all-weather approach and landing. The pilot is the aircraft commander with the responsibility of monitoring aircraft performance and successfully completing the approach and landing. The copilot's role is managing the automatic equipment and checking its satisfactory operation.

Aircraft

In addition to the electronic systems installed in the DC-9 aircraft for Category II operation, the aircraft itself plays an important role in achieving all-weather operation. Aircraft handling characteristics, stability, performance, and control must be considered to ensure safe operation with a Category II system.

The installation and mounting design of the twin engines on the fuselage of the DC-9 aircraft minimizes the effect of a large thrust change or loss of an engine on the trim of the aircraft. Careful design of engine installation positions the thrust line to eliminate pitching moments caused by changes in thrust. Mounting the engines on the fuselage reduces the magnitude of the yawing moment incurred when an engine fails.

The DC-9 mechanical flight control system is cable-controlled and designed so that no single failure can result in loss of control of the aircraft. The pitch, roll, and yaw systems are duplicated from the cockpit to the control surfaces to provide redundant control paths. All the control systems are designed for simplicity, maximum reliability, and minimum maintenance.

The flight compartment of the DC-9 aircraft is designed for a two-man crew with all systems controlled from either seat. This allows each operator greater flexibility in developing cockpit procedures for low approach and landing operations during adverse weather conditions.

During an approach in adverse weather, at the critical altitude of 100 feet the pilot must be able to make visual contact with the ground or execute a go-around maneuver. In order to provide clear visibility through the windshield, electrically heated glass is used for defogging and anti-icing. In addition, rain removal from the windshields is accomplished by an electric wiper. Minimization of reflection from light sources both inside and outside the aircraft is provided by a glareshield.

THE NEXT STEP

To carry the all-weather landing system capability below the 100-foot ceiling minimum, the flight director,

instruments, and system monitor must display the approach situation with a high degree of accuracy and reliability, and in a form suitable for rapid assimilation and correct interpretation by the pilot. In addition, highly accurate, stable, and reliable automatic systems which the pilot can utilize with confidence are required. These requirements are met in the Category II system discussed in this paper. In addition, the system is designed to:

- Allow maximum use of system components prior to their use in the critical period of the approach and landing so that the pilot can continually assess the equipment performance throughout the flight envelope.
- Minimize switching of vital circuitry close to the ground to prevent switching malfunctions at low altitudes.
- Prevent rapid maneuvers close to the ground by limiting attitude and rate commands.
- Provide compatible automatic pilot and flight director modes and switching to facilitate monitoring.

Therefore, this Category II system will not be obsoleted when the final goal of Category III Operational Performance is realized. On the contrary, it will smooth the road to all-weather touchdowns, since the only guidance elements this Category II system lacks are the flare and de-crab computers. Most certainly the equipment used in a Category II system will also be required in a Category III system. The point in question concerns the accuracy and reliability required in the two systems. The requirements may be the same for the two systems, but more stringent proof of meeting the requirements may be required for the Category III system. With the implementation of this Category II system in turbojet aircraft, system accuracy and reliability figures can be compiled to determine what modifications and/or new equipment, if any, would be required to meet Category III airborne equipment requirements. In addition, pilots will be given an opportunity to familiarize themselves with the equipment which will ultimately be used in an all-weather landing system. This will allow them to gain confidence in the system components before they rely on the equipment to land the aircraft.

**THE PRACTICAL DESIGN AND TESTING OF THE AUTOMATIC
MONITORING SYSTEM IN THE VC 10**

Presented by

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at the

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Summary

The prime requirement of any fail-safe or failure-survival system is failure detection. This paper discusses some of the practical techniques used in the design, analysis, and testing of automatic landing systems for the Vickers VC 10 and BAC 1-11. It is argued that in the future electronic and auto-control equipment must be designed so that assessment of its fail-safety can be made with the same degree of confidence as safety analysis on the aircraft which carries it.

The paper assumes that the reader is broadly acquainted with the overall system concepts in the VC 10 and BAC 1-11 which have been outlined recently at the IATA 15th Technical Conference.

Introduction

Automatic monitoring is a design feature of each of the two autopilots in the VC 10 installation. The prime object is to enable the detection of significant failures in either of the automatic control systems. Two such monitored autopilots can then be used as a failure survival combination by providing automatic changeover from one to the other. This is the basis of the automatic all weather landing system in the VC 10. It is illustrated in the block diagram of fig. 1, but will not be described further in this paper, which is limited to failure detection principles and practice.

1. Categories of Automatic Monitoring

Automatic monitoring in the context in which it is used in the VC 10 is in fact automatic failure detection and the design techniques involved fall into three major categories:

- | | |
|---------------------|---|
| <u>Category 'A'</u> | The measurement of various system parameters with some external test device (absolute measurement). |
| <u>Category 'B'</u> | Comparison of the device or system with a second device or system performing the same or a similar task concurrently with the first (comparison monitoring). |
| <u>Category 'C'</u> | Overall measurement of performance of a task using some measuring means which is suitably independent of the device or system being checked (performance monitoring). |

All means of failure detection involve either a measuring or a comparison process and a failure of the measuring or comparison device is always

undetectable from a failure of the device being examined, unless a third suitably coherent device is also available and is used in such a manner that similar failures cannot occur in two or more of the devices at the same time. That is, any direct or indirect cross-connection required to allow the measurement or comparison to take place, must not introduce cross-dependence.

The exclusive use of any one of the three techniques is either impossible or undesirable and a combination, depending on the particular elements and the circumstances in which they must each be used gives the most economical solution.

In relation to category 'A', for example, the presence of an electrical voltage or hydraulic pressure can be detected and measured with simple automatic instruments. Similarly by absolute measurement one can check signal line and power circuit continuity, load and source impedances, radio carrier transmission levels, modulation depths, relative gain and phase, etc. However, a complete failure detection system based on such principles if possible would be very complex indeed (fig. 2 (a)) and it would be extremely difficult to prove that there were no failures which could go undetected, especially between the measuring points. Perhaps the greatest difficulty however, is making any sort of assessable measurement when the system is in a dynamic state. For example, the computation of an exponential flare-out demand from radio altimeter signals would be impossible to check by direct measurement as it occurs, and the direct assessment of independent flare path or rate of descent measurements is also too difficult in this critical manoeuvre. It is possible in certain cases to inject an excitation signal into part of a system, assess its effect, and then cancel it before it appears as an output (fig. 2 (b)). This technique of absolute response monitoring has been investigated for "on-line" checking of simple yaw dampers but usually it is more economical and certainly more complete to use the "comparison monitoring".

This is covered by Category 'B'. By comparing the computer demands with the output of a similar perhaps identical independent computer it is possible to assess whether the demand computation is within the pre-determined acceptable threshold. Fig. 3 shows block diagrams of simple systems employing such principles from the sensor elements (separate or monitored) through to the actuator outputs. A vital advantage of this technique is the simplification of the analysis necessary to prove that the failure detection means is valid for all significant failures, because provided there is no common failure probability, most of the design details are now immaterial to this, and affect only performance standards. In fact it is only aspects of this type, such as the comparator and disconnect device itself, which must be subjected to detailed investigation. It should be clear however that a complete failure detection system based on this concept (equivalent to "duplex" or "double-redundant") would be very uneconomical as certain aspects can certainly be simplified by other failure detection means.

Finally, Category 'C' covers modes of operation of both single devices and full systems which lend themselves to overall performance checking. For example, a simple case is that of a feedback servomechanism which if operating correctly will not develop an input-output error demand greater than a certain value in a given time, this being a function of the type of input which it receives. This value can be constantly checked and this constitutes a failure detection means. (This is in fact the manner in which the output servos are monitored in the systems of fig. 3.) On a broader scale this principle can be applied to autopilot "hold" facilities, say for example, a height lock where a deviation from the height originally selected by more than some predetermined amount measured on an independent sensor, can be taken as a failure (fig. 4). In this example it is important that the failure detection circuit is independent and various additional precautions are taken such as having a mechanical bias applied to the monitor sensor pick-off to avoid the possibility of missing a failure on a normally "null" circuit.

2. System Applications

These automatic failure detection techniques have been widely used in the system designed for both the VC 10 and the BAC 1-11. As a further example an automatic throttle control system is illustrated in fig. 5. The airspeed P-S capsules and pressure sources are fully duplicated along with their pick-offs, but there is only a single pick-off/amplifier and motor/gearbox follow up system, as any possible failure up to the output shaft of the gearbox, including jamming, will cause an output error to be developed in the second pick-off, which comprises the failure indicator. This does not cover failures such as stripped gears or loose couplings as it is considered that between normal inspection and overhaul periods the probability of such failures occurring would be adequately remote. This particular design employs only low power motors and mechanical design features such as duplicated gear pins and hence this low failure probability is a reasonable assumption. The output shaft has twin output synchros, each referenced from twin transmitter synchros in an airspeed selection controller. One synchro transformer feeds the airspeed error signal to a computer and amplifier where it is combined with a pitch angle stabilisation term. (As part of the main autopilot pitch system the main vertical gyro is also continuously compared for verticality with a second monitor gyro.) The second synchro transformer is an airspeed error detector. A study of fig. 5 will show that if any airspeed error occurs which is not merely a short term perturbation this can only be due to an internal failure, and hence in the system described, an assessment of airspeed error is the failure detection means. Similar automatic failure detection means can be integrated into the design of most airborne equipments. For example, fig. 6 is a block diagram similar to one half of the VC 10 autoflare system, which uses automatic monitoring to a more elaborate degree from the ILS receiver and radio altimeter through to the aircraft power controls. All categories of automatic monitoring are employed in a fairly economical arrangement. For example the ILS receiver uses a form of absolute measurement of the A.G.C. circuits in the pure receiver stage to assess the carrier and its modulation, while the output filter stage is fully duplicated and assessed by comparison

monitoring. Similarly, one version of the radio altimeter employs a transmitter absolute monitor but has duplicated receiver elements which are compared for failure detection. The control computers are duplicated, although some simplification is possible in the monitor unit. The vertical gyro is directly compared with a second gyro but carries all multiple outputs from different pick-offs on the main gimbal output or from output repeaters. As in fig. 3 the servo is performance monitored from an input-output error assessment. This system differs slightly in concept from that of fig. 5 in that it is purely an aircraft equipment monitoring scheme, which takes no action if there is any inadequacy of overall performance. (The automatic throttle system of fig. 5 as well as providing cover against equipment failures, can take action if there is an inability to hold the airspeed, as airspeed error is included in the monitoring loop.)

3. Failure Analyses

If automatic control equipment is to be of maximum use in the future, then it will inevitably assume limited responsibility for certain aspects of aircraft safety, and in such cases, it is vital to know whether or not the equipment concerned is operating correctly, and whether the failure detection means can in any way be negated. The assessment of probability of correct operation must rely heavily on failure analysis, but unfortunately with more complex systems this is becoming virtually impossible, as the number of failure modes and combinations can reach astronomical figures. However, the use of comparison monitoring, which usually represents a major proportion of any automatic monitoring system, by its very nature, simplifies the problem of failure analysis. In fact only those points in a system which are vulnerable to common failures affecting both a main control lane and a monitor lane simultaneously require detailed analysis. Even then, if a common failure is shown on analysis to give a positive disconnect it can be acceptable. For example, referring back to fig. 5, the number of points requiring detailed failure analysis are, the common Airdata gearbox, the vertical gyro output drive, the controller selector drive shafts and gears and the comparator, which must be so designed that any failure within itself causes the monitored system to disconnect. This must include the possibility of a widening threshold in the disconnect logic circuits due to component drifts as well as disconnect failures. It is essential to account for this in design so that no dormant failure in the disconnect device can prevent a serious system failure from being detected immediately it occurs.

It will be realised that even this limited amount of detailed analysis is more elaborate than implied by fig. 6, as all aspects of aircraft installation and interwiring are involved. Fig. 7 illustrates the magnitude of the task in practice. This is an interconnection diagram for one monitored autopilot, i.e. one half of the VC 10 installation. The vulnerable areas, as stated before, are those where there are potential cross connections between the comparison and main autopilot units. These areas are indicated at the interface of the main autopilot and comparison sections in the diagram. Typical examples are power supplies

to the comparison pick-off elements in the Air data sensor and throttle and autopilot controllers and corresponding signal lines from these comparison pick-off elements back to the comparison computer itself. However, the amount of vital failure analysis required can be seen to be trivial in relation to what would be involved if the complete system were not covered by automatic monitoring facilities. In fact the task would be impossible in practice if every individual element were subject to detailed analysis of all of its failure modes -- even if they were known. The simplification of failure analysis is very important as there is no other means to assess whether a system will meet the low failure probabilities now being sought as no significant amount of in-service operational experience can ever be obtained.

4. Fail-safe Design

The precautions taken in the VC 10 equipment design to ensure that the possibility of vital failures is avoided are very extensive. In fact, in all cases where there was any doubt the most positive, if somewhat uneconomical, solution was adopted, that of full duplication, even though this is not always compatible with the reduction of gain tolerance problems.

Some typical examples of the practical precautions taken in the design of both VC 10 and BAC 1-11 all weather landing systems equipment are as follows:

- (a) All "autopilot" and "comparison" signals and power supplies are taken through separate connectors so that the possibility of pin to pin, pin to shell, or other common electrical failures between the two control and information lanes is avoided. The one exception to this is the Marconi ILS glide slope receiver which has the two separate filter outputs on the same connector. This was desirable in order to maintain ARINC standardisation and it is permissible because detailed failure analysis has shown that no common failure is possible which does not also cause a system automatic disconnect. This is an example of a general case mentioned before in which common failures between autopilot and monitor channels are permissible!
- (b) Separate power supplies are provided for main autopilot and monitor elements. This ensures that no common power supply failure can go undetected, even for the briefest period. Where power sources ultimately come together, as required by main electrical system protection arrangements, a limited, but adequate number of power failure detector switches are employed. In the main however, separate power supplies are necessary, as the majority of failures are in the class of open circuit secondary windings on transformers, and such-like, and these will rarely reflect a sufficient change in load to operate a busbar power failure switch.

- (c) Comparator/disconnect devices are required in several places in the VC 10 system and these have been especially designed to be fail-safe. That is, any internal failure, must cause a disconnect, just as if it occurred within the autopilot or monitor lanes. The alternative is to have a failure survival comparator device which will continue to work, by means of redundancy, following a failure. Unfortunately, such a device requires regular checking to determine its redundancy status and this is considered to be a serious disadvantage. (In newer designs a partial failure indicator technique has been developed to overcome this difficulty using electroluminescent panel indicators on the computer boxes, but this is not suitable for the VC 10 or BAC 1-11 installation.)

To obtain the required degree of fail safety in the comparator/disconnect requires very careful design and the scheme adopted by Elliotts is illustrated diagrammatically in fig. 8. It comprises two non-linear amplifier input elements, carrying autopilot and monitor lane information respectively. These are compared and within the limits of equality specified, the comparator element outputs an AC signal. This in turn excites a "zeroquiescent" bistable amplifier which oscillates and energises a pair of engage/disconnect relays so long as the excitation is present. If the excitation disappears due to an error arising between the autopilot and monitor, or due to an internal failure anywhere in the comparator device, including open circuit wiring or widening of the disconnect threshold loci, then the amplifier will cease to oscillate and the duplicated relays will drop out causing a disconnect. Similar fail-safe characteristics can be obtained by other methods but the particular design described is very stable and holds disconnect thresholds under normal operating conditions to about $\pm 3\%$, even in the presence of drift of component values over the life of the equipment.

- (d) As stated before any comparator/disconnect device is vulnerable to common failure problems and this applies equally to the autopilot engage circuit of which the comparator/disconnect switch is an integral part. For example, any "hang-up" in the engage circuits after the comparator has signalled a disconnect could be very serious, and any possibility of this must be completely eliminated.

To this end a completely new engage circuit concept is used in the VC 10. The basis of this is a "floating" power supply separately derived and independent of the other autopilot supplies. This supply is 115 V. d.c. and the circuit is of such an impedance that it cannot be effectively energised by any other aircraft supply through any "fault" or "sneak" path. In any case, two coherent failures would be necessary to effect any "hang-up". In addition, parts of the circuit are duplicated and

all relays have been designed to have exceptionally high residual holding voltages so that there is no tendency to hold in other than when correctly energised.

- (e) All wiring and intercabling from the separate autopilot and monitor connectors is kept separated as far as possible but where common cable ducting is used a dielectric barrier is imposed between the two bundles of wires.
- (f) Autopilot and comparison manometric information is obtained from separate pitot heads and static vents so that simultaneous failures of both control and comparison lanes due to such problems as icing or insect or bird blockage is avoided. This is important to all weather landing in relation to auto throttle control requirements.
- (g) The pilots' controllers, both main autopilot and throttle, have separate sections, mechanically and electrically isolated, for autopilot and comparison monitor demands. The autopilot controller is illustrated in fig. 9 and its Roll and Pitch section is shown in fig. 10. This is a dual controller but the main elements of one of the monitored autopilots are in full view. The pitch wheels connect through a worm gear to a clutch which couples the drive to a pair of ganged and matched pitch potentiometers. With the coupling clutch disengaged the potentiometers are centred with a spring loaded cam mechanism.

The important requirement of this mechanism is that any failure which could endanger the operation of the aircraft when on autopilot must cause an immediate automatic disconnect. In the case of the manual pitch controls, when the autopilot is engaged in one of the lock modes or in autoflare, the coupling clutch is de-energised and the centering solenoid is disengaged from the ganged potentiometers. These are then held in the trimmed position which exists on engaging the mode by means of a brake. Hence, if energisation of the centering solenoid fails the centering cam and follower will cause the ganged potentiometers to snap to centre simultaneously. Hence both the autopilot and monitor channels will receive the same input and on the face of it no disengagement will be demanded, although due to the failure the autopilot will be subjected to step input pitch disturbance. In fact due to a small difference in high frequency response between the autopilot and monitor channels, a disconnect will probably occur, but something more certain is necessary without having to adopt the grossly uneconomical solution of complete duplication of everything. In fact, the principles outlined in the foregoing have been applied and the design precautions taken to ensure this complete failure detection capability are as follows: First the pitch wheels are double locked to the worm pinion shaft and the mechanism is stout enough to be adequately failure-free. All bearings are

exact fits in the main castings (not interference fits) so that even if an inner race jam was experienced at any point a reasonable excess pressure would cause an outer race to rotate on the main casting.

The further working principles of the pitch controller can be seen by reference to the circuit diagram on fig. 10. When the autopilot engage switch is depressed the centering clutch is energised which releases the centering cam follower and in the same motion applies a light brake to the centering cam. This movement also operates a microswitch which completes the engage interlock circuit and allows the autopilot to lock into engagement, while at the same time the microswitch action inserts a resistor into series with the coil of the centering solenoid in order to reduce its current drain to holding level only. Also at the same time the coupling clutch is energised and pitch inputs can be applied via the pilots pitch wheels. When the further modes such as auto-flare are selected, the coupling clutch is de-energised, leaving the ganged potentiometers in the position existing at the time of selection, held by the brake.

Now the effect of failures can be examined. First, taking the example already mentioned, if the centering clutch fails, the two ganged potentiometers will snap to centre, but at the same instant the microswitch will break the engage interlock circuit and the autopilot will disengage as required. Now consider a failure of the microswitch in the operated position, due to say a welding of contacts, or a jammed plunger. Then on the first occasion that the autopilot is disengaged and then later re-engaged the centering clutch solenoid will drop out, but cannot be brought in again due to the current restriction of the series resistor. Now the centering torque of the cam and follower in the detent position is deliberately very much larger than the torque which can be carried by the coupling clutch and hence in this case the potentiometer cannot be moved by operation of the pitch wheels. Hence there are now two desirable situations. First the ganged potentiometers cannot be put off-centre again, which could be dangerous on subsequent engagement of a lock mode, and second, the pilot will discover that his pitch wheels are not effective and will "snag" the system, which will result in the failed microswitch being discovered. The probability of a dangerous combination of failures, resulting from a failed microswitch and a centering clutch failure in the same critical period of a flight is tremendously remote. Similarly failures such as shorted external terminals on the microswitch can be avoided by design and manufacturing precautions and in fact further detailed analysis will show that all other possible failures cannot escape detection and the overall fail-safe requirement is met.

This is an important example of failure analysis of simplified designs which use a minimum of redundancy. The example also illustrates clearly the type of design action which can be taken to force "so-called" dormant failures to reveal themselves. These are failures which do not affect the immediate operation of the system, but which remove any element of redundancy or other safety cover which could leave the system at the mercy of a subsequent failure.

The seven examples above were chosen to give a cross-section of the type of problem involved in the design of systems with automatic failure detection facilities. More information on the overall concepts is available from papers in the list of references.

5. Nuisance Disconnects

The pursuit of simplicity in automatic monitor system design reflects directly into the level of nuisance disconnects likely to arise due to differences in the characteristics of the automatic pilot and monitor lanes. Normally the simpler the system the higher the nuisance disconnect level. This is minimised in the VC 10 by the fundamental concept of monitored system design which employs cross comparison between like elements, rather than complete signal chain comparison, and also by the techniques of signal consolidation (see references 1, 2 and 3). However, limits must be put on the levels which are acceptable and these differ considerably on whether or not failure-survival is required. For example, a nuisance disconnect of a single fail-soft system installation at the wrong time can be very embarrassing, if not dangerous, whereas with a fail-operative system, like the duplicated monitored installation as in the VC 10, it would be classed merely as a form of failure of the first system which would demand an autochangeover. In this context so long as it did not occur at a rate more than once per 50 hours operation it would be perfectly acceptable from the safety viewpoint -- although not by any means acceptable for serviceability and confidence reasons. In practice the VC 10 system calls for a minimum nuisance disengagement level of one per 1000 hours for each cross-monitored section of each half of the complete installation which gives a considerable safety and confidence margin.

There are cases where design actions are taken entirely to alleviate the nuisance disconnect problem. For example, a well known one is the case of rate gyros in roll and pitch control axes. The type of rate gyro used in the VC 10, in conjunction with its bandpass input filter, cannot develop a dangerous demand due to a failure and the effect of a failure does not result in anything more than a less comfortable ride. Hence it is unnecessary to detect the failure rapidly and hence duplication of the gyro for monitoring purposes is not economic. However, the effect of the rate gyro input to the main autopilot control chain can create, under certain disturbance conditions, sufficient dynamic difference between the two information lanes to cause an automatic disconnect. The solution to this is to cross-feed the rate gyro information used for control purposes into the monitor chain so as to eliminate any

discrepancy. This unfortunately then gives a possibility of a common failure in the autopilot/monitor combination, but in the VC 10 installation tests carried out with all conceivable types of failure have given acceptable results. In future designs a twin pick-off monitored gyro may be favoured and development of such units is proceeding.

6. System Testing

In relation to the VC 10 programme a considerable amount of ground testing has been completed using actual autopilot and monitor equipment on the Vickers "Iron Bird" rig. This has covered all flight conditions and modes of operation. Assessment of the rig when in operation has been effected by plotting continuously against each other the main autopilot and comparison demands on a background of disconnect threshold settings. This gives useful information in that the number of occasions a near disconnect is obtained is assessable and from the predications on actual nuisance disconnect frequency can be made. An X-Y plotter is also installed in one VC 10 test aircraft for the same type of continuous recording assessment. A typical recording is shown in fig. 11. The ordinate is the comparison monitor lane output, and the abscissa the autopilot signal modified by the servo-actuation system inverse transfer function.

Conclusion

This paper has dealt with certain concepts and techniques related to automatic failure monitoring in airborne equipment and it assumes some previous knowledge of the overall VC 10 system concepts as outlined in the referenced papers. The techniques described are analogous to those which have been employed for many years in design of aircraft structures, engines, flying control systems and many others. When such techniques are more widely used by autopilot designers, it may be possible to increase the reliance placed in these systems, even to the extent of allowing them part responsibility for aircraft overall safety.

It is our experience that although these techniques are often simple and easy to apply in theory, they are not always easily achieved in practice, as one design nicety can so easily be negated by another seeming refinement. It is essential to maintain very critical control over manufacturing, inspection and service requirements and to ensure that no common failure possibility creeps into a design, and only when complete engineering and design organisations, in both equipment and aircraft companies become familiar with the failure detection design techniques do the best and safest systems emerge.

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3. Dual Output Localiser and Glide Slope receivers for monitored auto-pilot systems by L. R. Mullin, Marconi's Wireless Telegraph Company Ltd., I.A.T.A. 15th Technical Conference Paper No. WP-145.

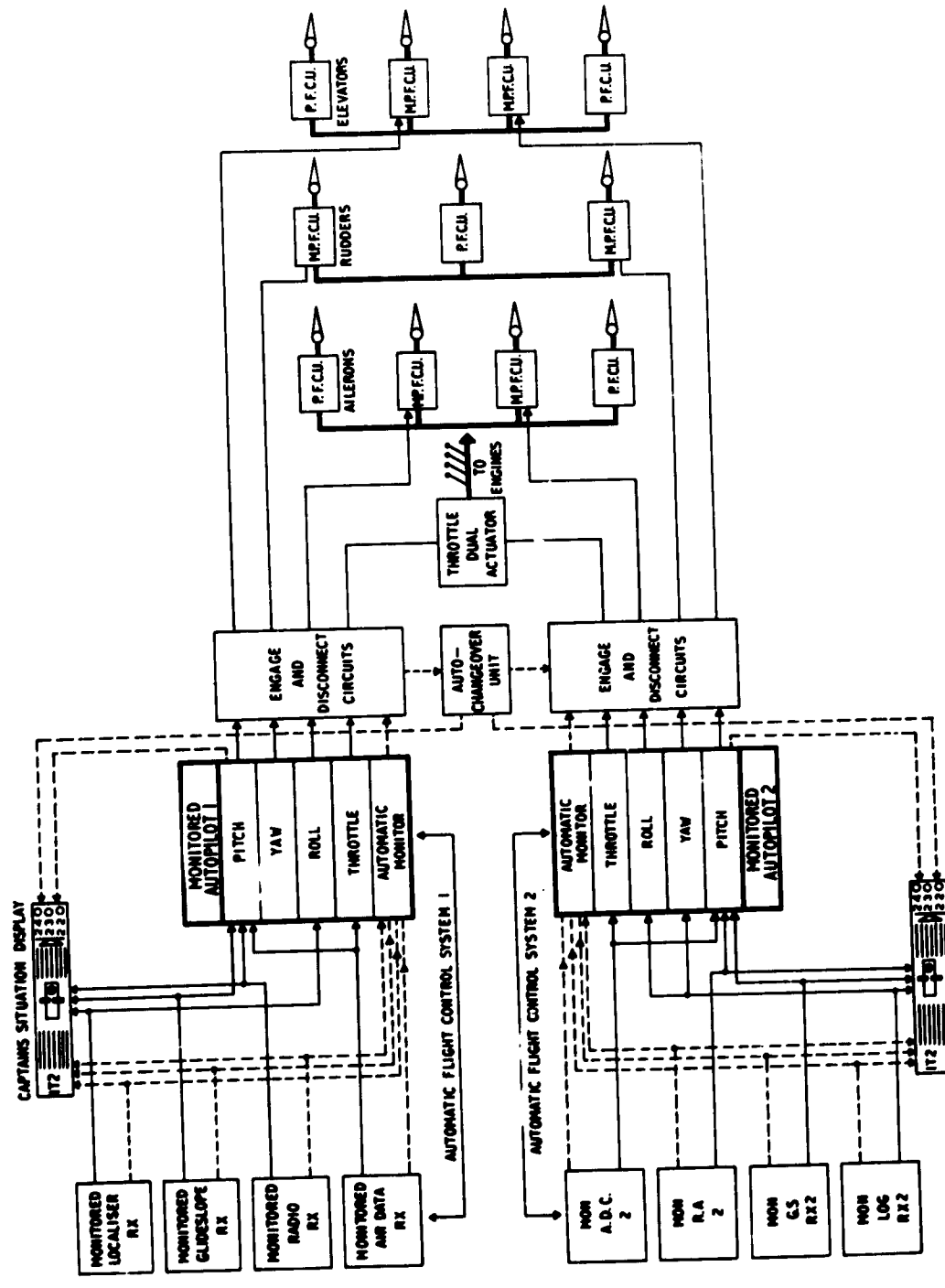
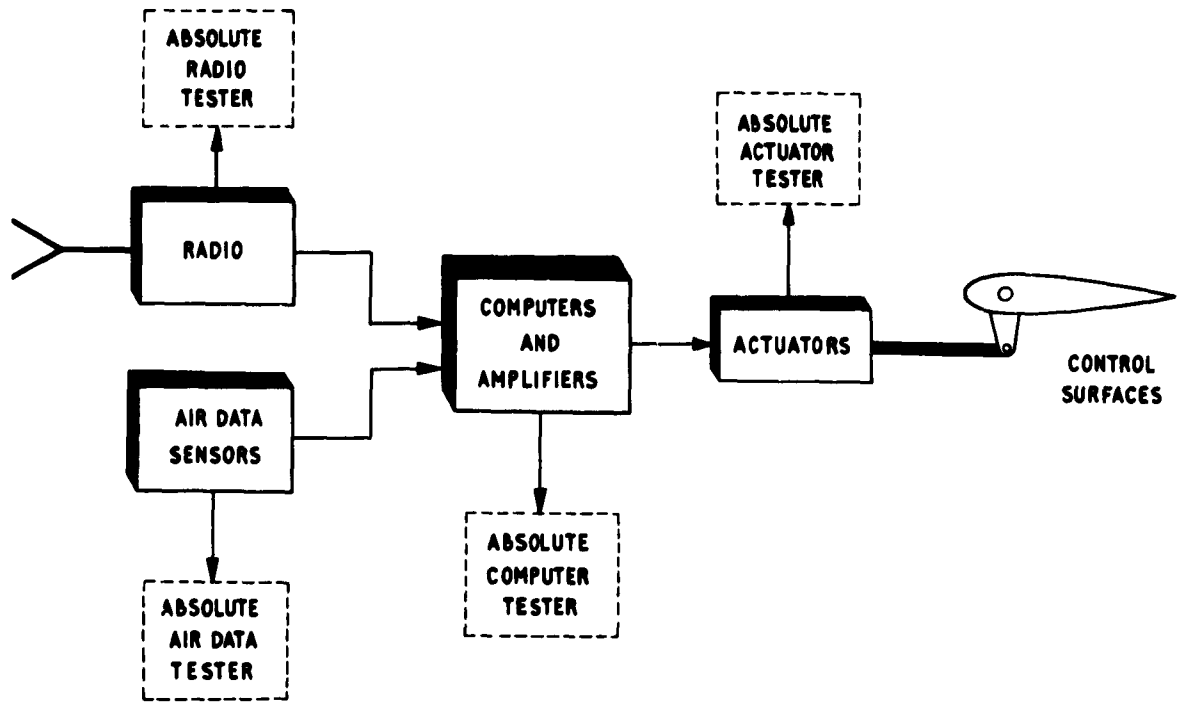
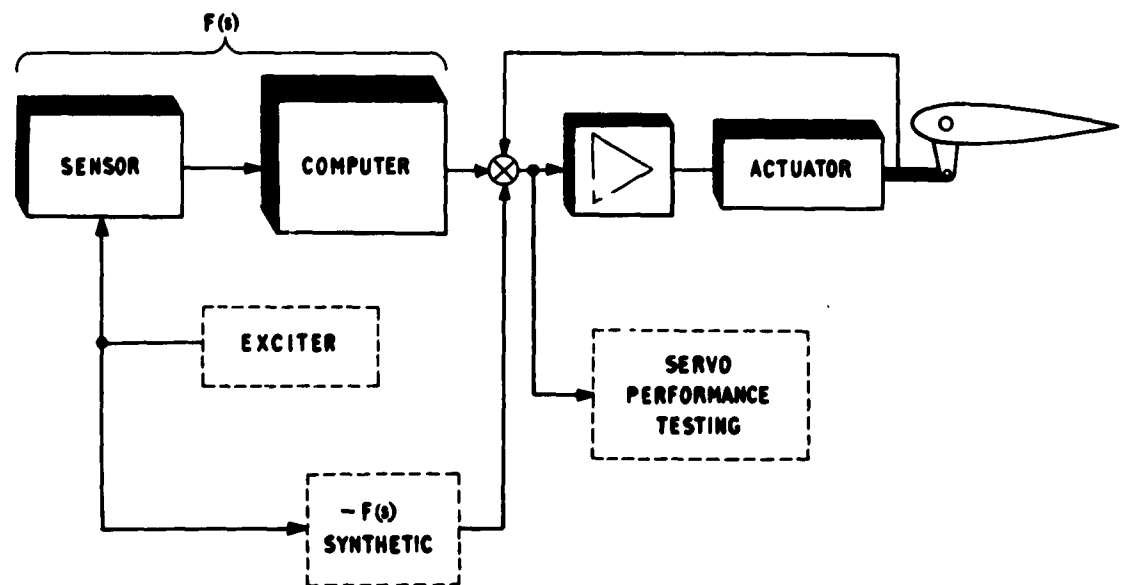


FIG.1. THE DUPLICATE MONITORED SYSTEM IN THE VCIO



(A)

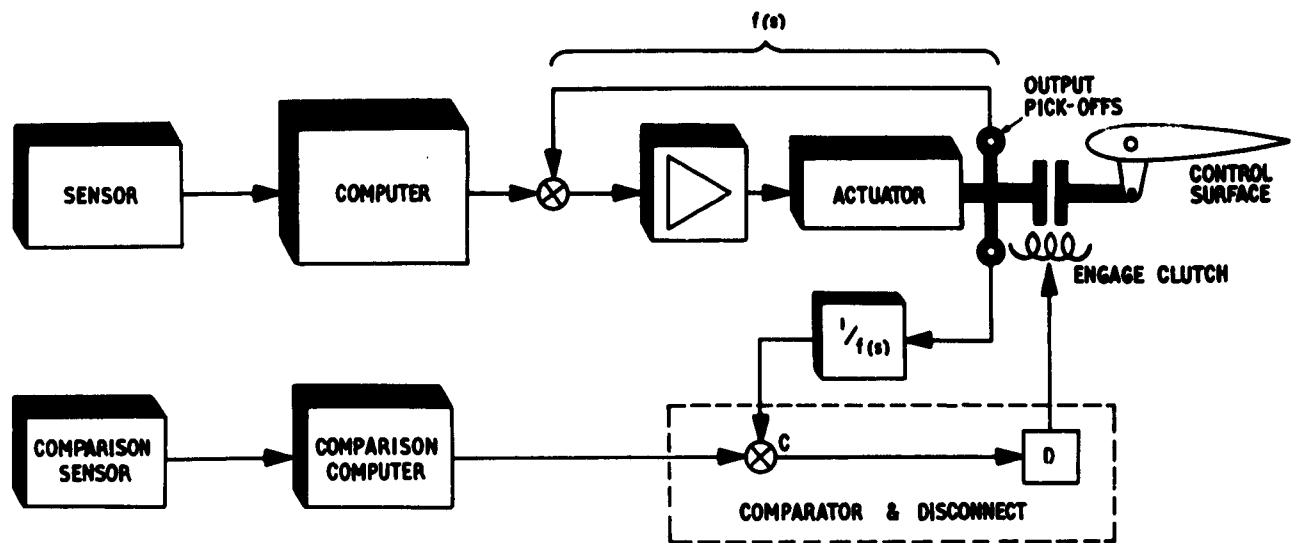
INDIVIDUAL EQUIPMENT TESTING



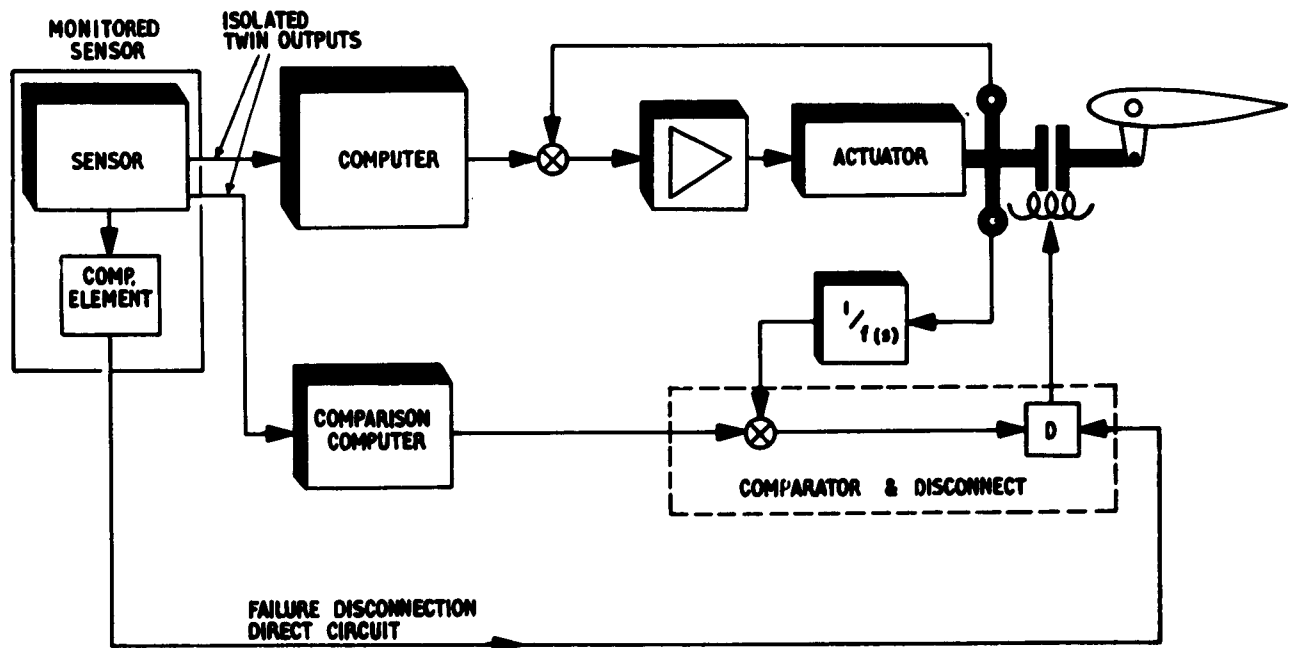
(B)

SERIES EXCITATION TESTING

FIG.2 FAILURE DETECTION SYSTEM USING ONLY ABSOLUTE MEASUREMENTS



(a) WITH SEPARATE COMPARISON SENSOR



(b) WITH A MONITORED SENSOR

FIG.3. COMPARISON MONITOR SYSTEM BLOCK DIAGRAMS

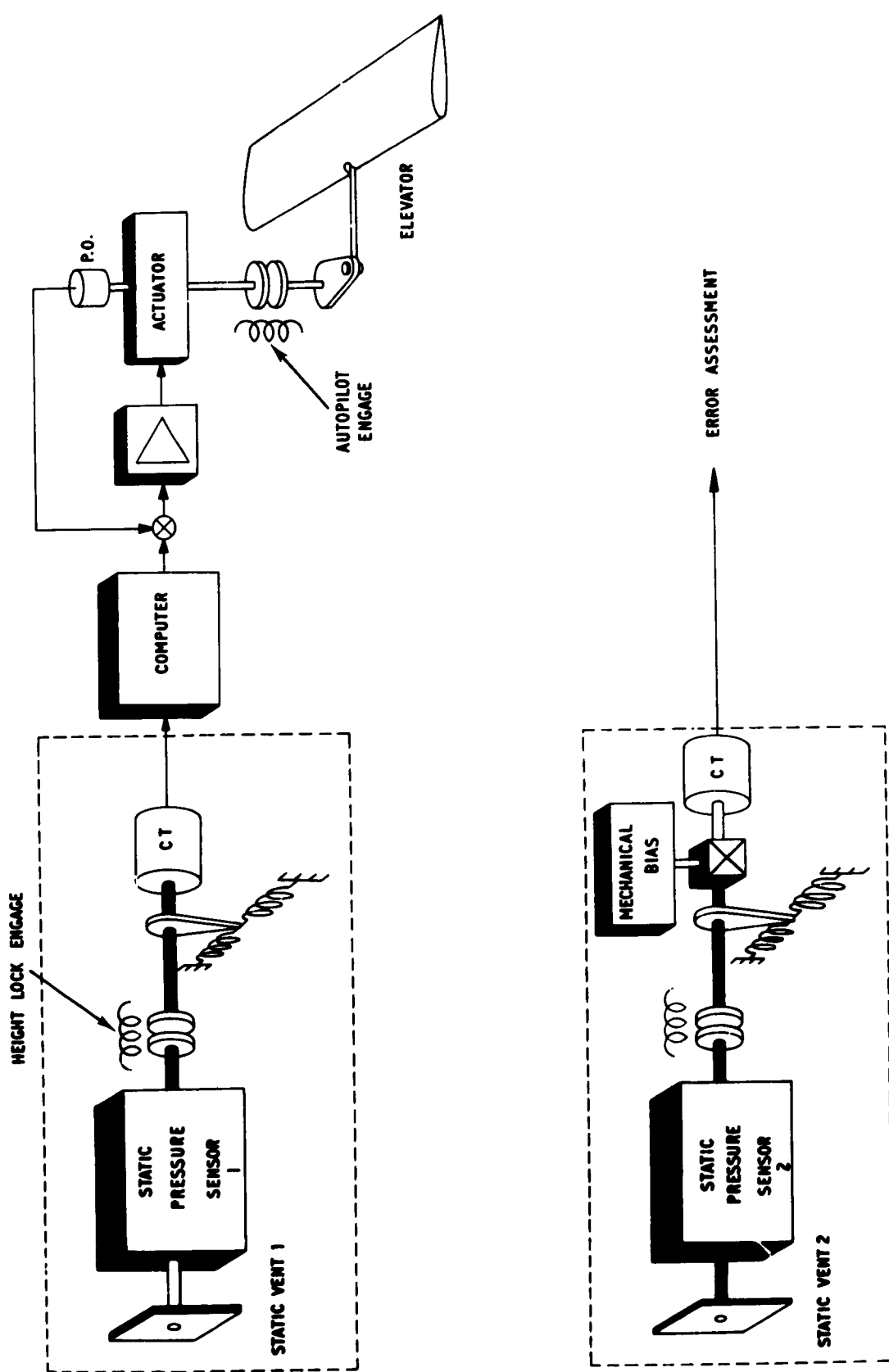


FIG.4 PERFORMANCE MONITORING OF A BAROMETRIC HEIGHT LOCK

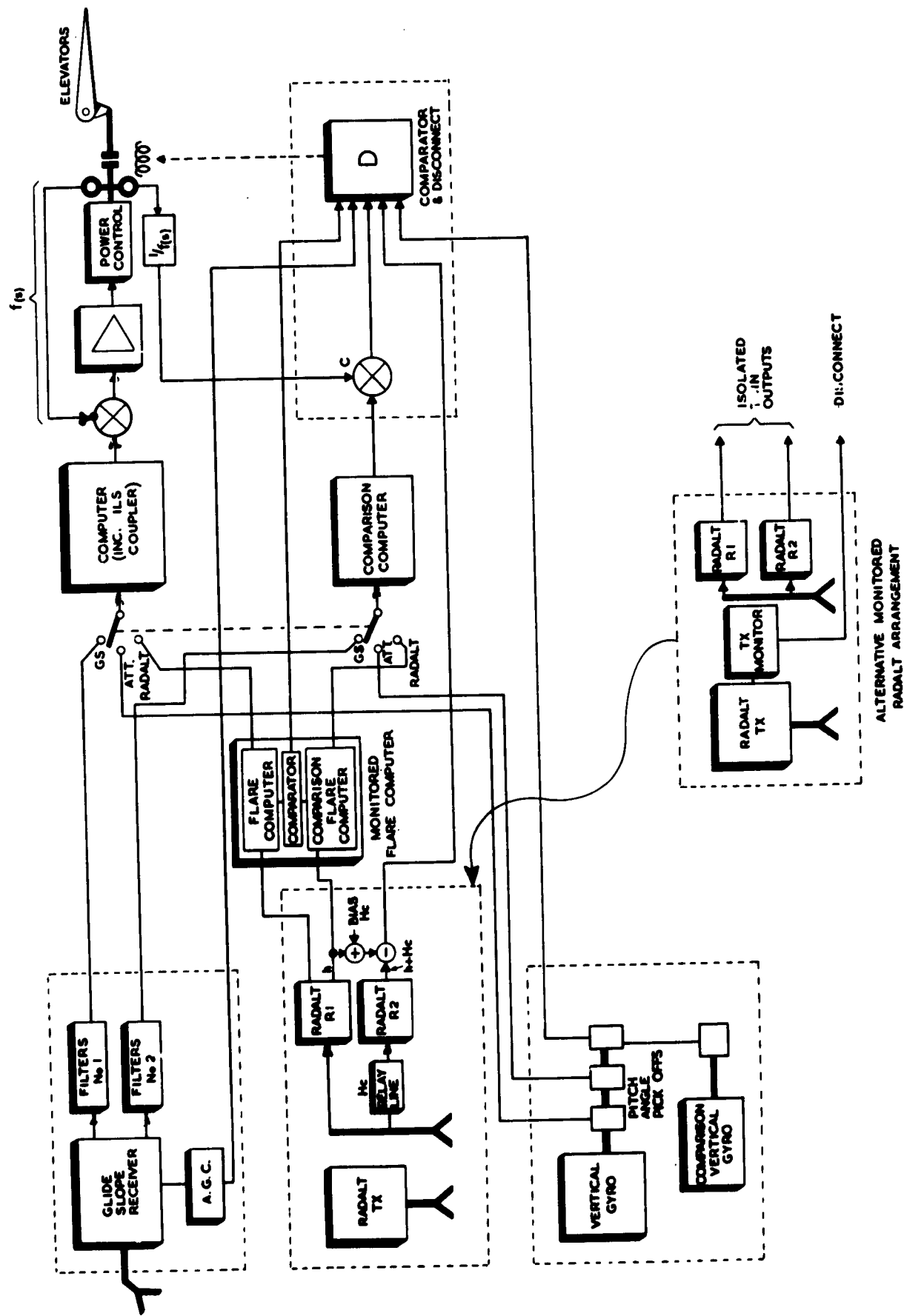


FIG. 6
A MONITORED AUTOFLARE SYSTEM SIMILAR TO
ONE HALF OF THE VCIO INSTALLATION

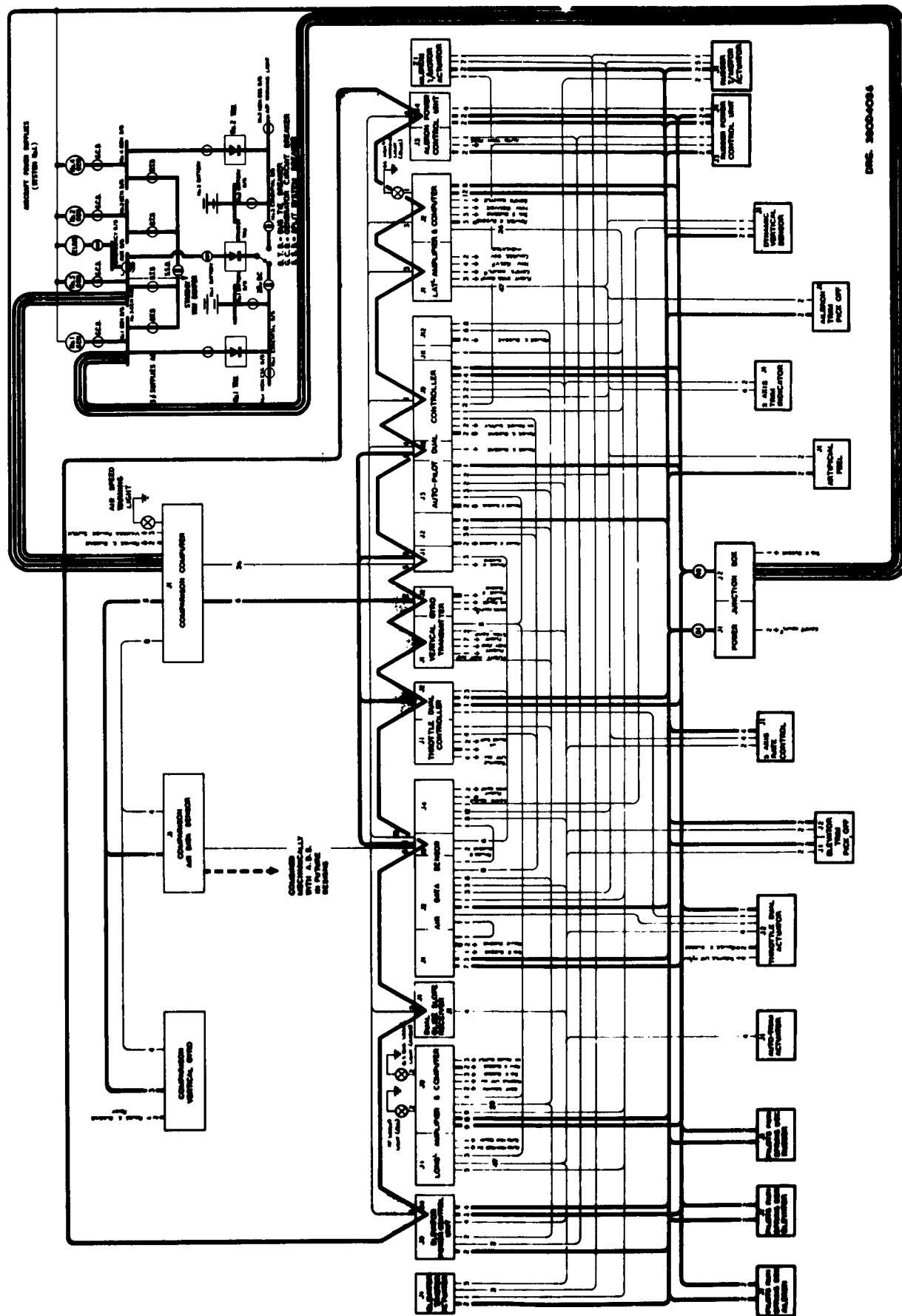
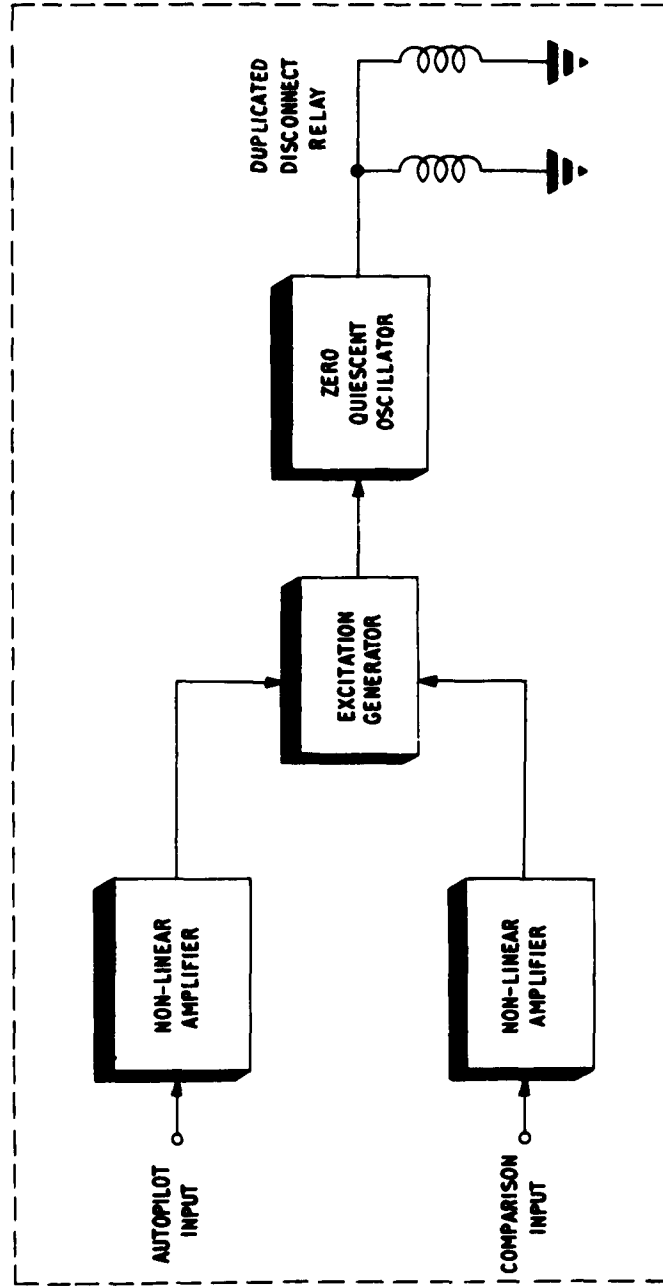


FIG 7 VC10 BASIC AUTOPILOT FAILURE ANALYSIS INTERCONNECTION DIAGRAM (No 1 SYSTEM ONLY)



**FIG.8 FAIL SAFE COMPARATOR-DISCONNECT
DEVICE**

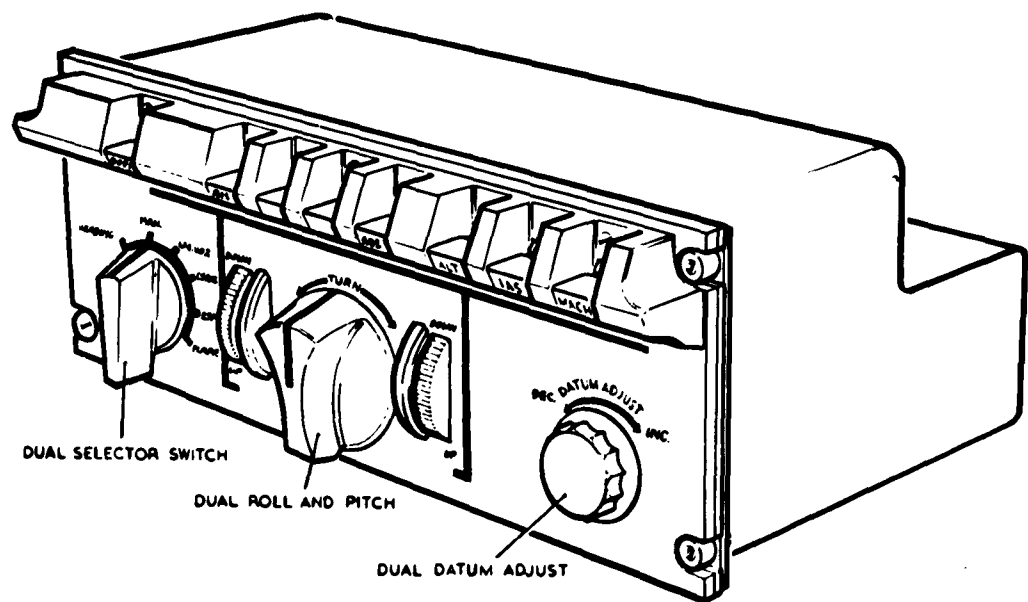


FIG.9 VC10 AUTO-PILOT DUAL CONTROLLER

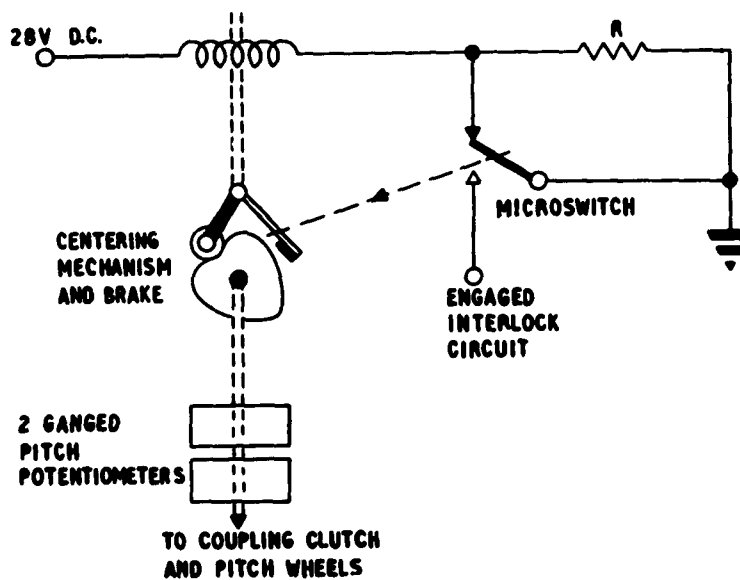
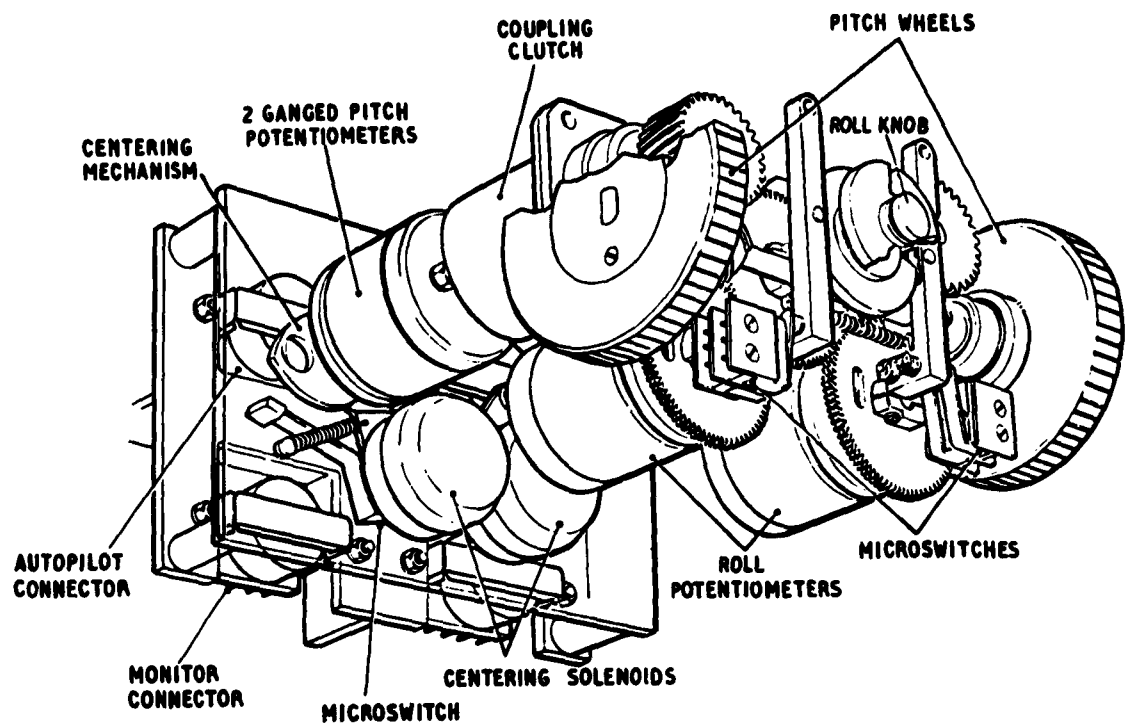


FIG. 10 DETAIL OF ROLL & PITCH CONTROLLER

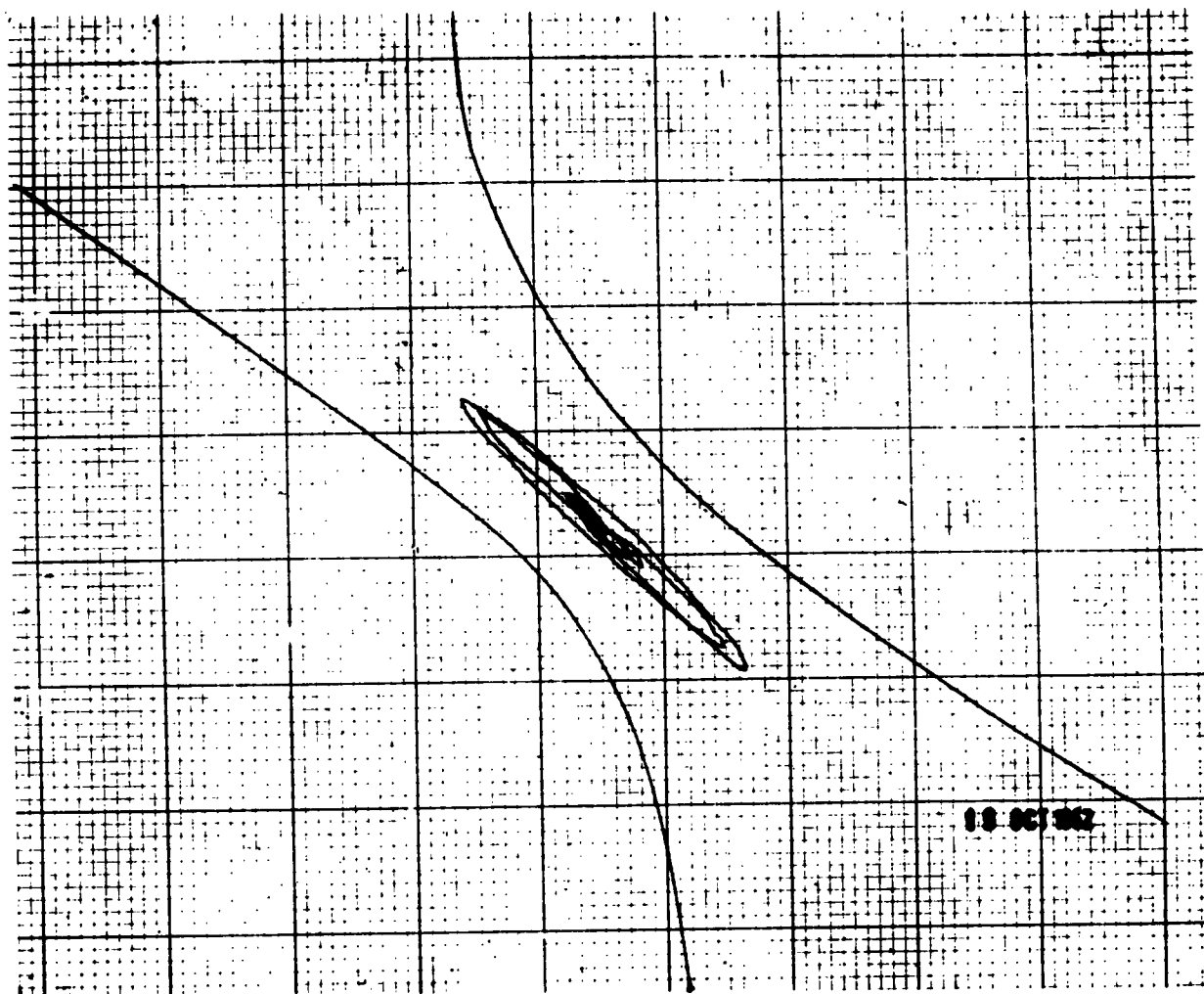


FIG. 11

**SAMPLE COMPARISON OF AUTOPILOT AND
MONITOR OUTPUTS**

THE BAC ONE-ELEVEN AND ALL WEATHER LANDING

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SUMMARY

The paper reviews the requirements for all weather landing systems on a short haul jet from the aircraft manufacturer's point of view, with, of course, particular reference to the BAC One-Eleven. The problems of producing a flexible system which will suit many different types of operator, with differing operational environments is discussed.

The basic provisions made in the aircraft and the basic automatic system for subsequent easy fitment of all weather landing systems are described and a number of possible alternative systems listed, which build up from the basic single autopilot to a fully automatic all weather landing system. The potentialities of each of these systems in terms of removing existing obstacles to lower minima are tabulated.

The major firm BAC One-Eleven development project - that of safe autoflare is described. This project is intended to result in the autoflare system being available for airline use in 1966.

It is recognized that systems which do not go as far as safe autoflare may confer some benefit - although the benefits to be obtained are hard to predict quantitatively - and may be attractive to some operators. On the other hand a fully automatic failure survival system will almost certainly be required to meet the full Phase III requirement. The ability of the BAC One-Eleven to accommodate this wide range of possible system requirements is described.

1. INTRODUCTION

The manufacturer of the short haul airliner finds himself subject to many opposing pressures today when the question of all weather landing facilities for his new project is considered.

On the one hand, he has to take note of the increasingly serious interest being shown world wide in the all weather landing problem, and the number of solutions being propounded - some of which are within comparatively short time of entering airline service. On the other, he has to appreciate that if his aircraft is to appeal to the small operator as well as the large, it must be as simple to operate and maintain as possible and inexpensive in first cost.

Because of the wide variety of operators, with greatly differing route structures and climatic conditions, who form the potential market, the systems designed should be flexible - that is, ideally they should be such that a number of alternatives can be offered which range from a

straightforward single channel autopilot only, up to a full automatic solution. The intermediate stages between these two extremes are difficult to define, but there is little doubt that, on an aircraft like the BAC One-Eleven, there is also a demand for something which will permit some lowering of minima without going all the way to full blind landing.

The economics of fitting an all weather landing system to a short haul jet are rather different to those on the larger long range machine. The safety standards must be just as high - perhaps higher because of the shorter average flight time and hence the greater number of landings made during the life of the aircraft. Hence to achieve the same objective, the quantity of equipment required will be the same. Whereas, however, the cost of the equipment may represent only three or four per cent of the first cost of a long range jet, it could represent up to nine or ten per cent on the short haul jet. This, of course, has a significant effect on seat mile costs and the economic benefits obtained must be correspondingly greater. Many attempts have been made by different organizations to obtain a realistic assessment of the benefits to be gained, from lowered minima, but the imponderable factors such as the growth of traffic which might result from improved regularity and safety make these assessments dubious. It is, however, reasonable to assume that improved regularity has a bigger impact on the economics of a short haul jet.

A prospective passenger can in general find alternative transport with much less inconvenience for a short stage. For instance, he is much more likely to drive his car from New York to Atlantic City if the weather seems dubious, than he is to change his air passage to sea if travelling from New York to London.

It is doubtful whether the true economics of the situation will be known until several years of operational use have been obtained, but it seems reasonable to expect that the balance of cost and revenue saving will be at least as favourable on a short haul jet as on a long range machine.

In addition to the influence of the general considerations outlined in the foregoing remarks, the philosophy of the BAC One-Eleven was, of course, inevitably influenced by the work on automatic landing carried out on the VC10. Although the circumstances of the two aircraft are greatly different, the background experience of automatic landing development work on the VC10 is a tremendous asset to the BAC One-Eleven. As is probably now well known, the VC10's first major customer, B.O.A.C., declared it's intention to specify a fully automatic landing system for the VC10 at an early stage of design, to be based on the B.L.E.U. principle, and to full civil safety standards. Military versions of the aircraft will also carry the system.

The BAC One-Eleven, however, had no such backing from a customer placing a large order in the early stages and the provisions made for all weather landing had to be based on BAC's assessment of likely requirements. It is no secret that a recent customer - Aer Lingus - has declared it's interest in automatic landing for the aircraft and that a firm BAC project now exists.

The main body of this paper describes the systems now under development and discusses the possible stages which are being offered.

2. SYSTEM PHILOSOPHY

2.1 General

Successful introduction of operations in worse weather conditions than are permitted today will not be achieved if there is any possibility of a deterioration in safety standards.

The task of winning the confidence of the travelling public, the certificating authorities and the airline pilots is not going to be easy.

The target for complete system reliability is that the maximum risk of a fatal accident when using the landing system should be one in ten million. Obviously, the achievement of the standard cannot be demonstrated absolutely in practice before the system enters service, but it should at least be demonstrable theoretically by rigorous fault analysis. Cautious introduction into service, with initial clearance to weather minima which are less severe than the final target, is envisaged with progressive lowering of minima as operational experience is obtained.

The likelihood of all-weather landing systems being specified for the aircraft had an impact on the basic design of the aircraft and also on the design of the basic automatic control system.

2.2 Effects on basic design

The BAC view on the ultimate (i.e. Phase III) all weather landing system solution is that it will involve system redundancy. To make the system redundancy concept valid, it must be applied to all links in the chain, including the mechanical control circuits and the electrical power generation system. Where the use of an unduplicated component is inevitable, the reliability of that component must be demonstrably so high that the standard is maintained. This is possible for certain mechanical elements.

Generating system

Fig. 2 gives a schematic diagram of the electrical generating system. A separate, normally completely independent power source is available for each of the duplicated automatic control systems which would be used in a full Phase III automatic landing system. This is consistent with the general philosophy of redundant systems. Most single failures in one generating system lead to an automatic switching of its loads to the second generator, thus avoiding an unnecessary changeover of automatic control systems. The exception to this is the failure of a bus bar, which would cause that generating system to become dead and an automatic changeover of automatic control systems to take place.

A third source of electrical power is available on the aircraft - from the A.P.U. - and it is possible that this may be used to improve the overall reliability still further in the ultimate system. It could for instance be used to allow automatic landing at the end of a flight during which a generator failure has been experienced.

Control circuits

The likelihood of mechanical failures within the control circuits of the basic aircraft during the landing phase has to be assessed and if any are found which are of comparable probability to a failure of an electronic system, the system philosophy is of course invalidated. In practice, this would be extremely unlikely since the basic aircraft would be unacceptable in this condition. Vulnerable mechanical elements in the control circuits of the BAC One-Eleven are duplicated. The main effect of the all weather landing system on the design of the control system was to ensure that the servo actuators of the duplicate automatics could be engineered into the circuit in such a way that no single control circuit failure could lose both automatic systems. For example, the auto-flare system required two pitch channels and the servos for each are coupled into the duplicated elevator cable circuits as shown in Fig. 8.

2.3 Basic automatic pilot system and its development potential

Fig. 3 is a block schematic diagram of the Bendix PB20D system as originally designed for the BAC One-Eleven aircraft. It differs in two areas from the PB20D system as installed in other aircraft although it includes TALL programme developments including the type 18729 amplifier computer. The two main differences of equipment are the stabiliser trim servo motor and the inclusion of the torque limiter adaptor unit. This unit, which is included in the pitch axis is a simplified monitor unit. It is utilised as a means of limiting the accelerating forces applied to the aircraft due to a "hardover" to one "excess g" or less whilst allowing the autopilot adequate authority to provide good performance in all operating conditions, particularly during coupled approaches. This authority level could, if a protection system was not provided, allow greater than one excess 'g' to be applied to the aircraft in a "hardover" condition. A conventional torque limiter would not provide adequate protection against this condition, particularly in the low speed flight case.

The T.L.A. unit, which incorporates signal limiters of air data and glide slope commands, provides the system with the basis of a "fail soft" pitch axis. The monitoring unit therefore provides a "low disturbance" disconnect protection system during low speed flight, i.e. during holding and approach phases in the pitch axis against "hardover" failures, but in order to provide a "fail soft" system of the type necessary for automatic approaches to low altitudes it is necessary to cover the "slow over" type of failure and to provide the full protection in both longitudinal and lateral axes.

During development investigations and design work it became clear that onward development of this system, as shown, to a fully monitored fail soft autopilot, with automatic throttle control, autoflare computation, failure survival in the pitch axis, and eventually a full failure survival automatic landing system, was not acceptable. It would be costly, would not be economic to maintain in service, and would not result in a good engineering job, in either the equipment or the installation. In addition, it would not be possible, without sacrificing interchangeability with other PB20 installations, to even approach the standard of integrity necessary for a " 1×10^{-7} " system. It was therefore decided to take advantage of Elliotts' and our own development work on the VC10 automatic landing system and utilise the separately packaged pitch axis and lateral axis amplifier/computers to replace the type 18729 amplifier computer, and to replace the type 4918 air data sensor with a modularised unit, to which extra modules are easily added to provide additional facilities, including self monitoring.

The basic autopilot system now consists of the units shown in Fig. 4. The changes made to the system still allow a large degree of interchangeability with PB20 systems at unit level, for example the servos and their mountings, the three axis rate unit and dynamic vertical sensor.

In addition, the longitudinal and lateral amplifier/computers, in the VC10 system contain a large proportion of PB20 card modules. When these units are applied to the BAC One-Eleven, this proportion increases to almost the equivalent of the Bendix 18729 unit. However, where development work on the VC10 system by Elliotts, or TALL programme improvements can be applied with advantage, then this is done. Some card modules will therefore be changed in detail design, to improve performance reliability or integrity.

The change to the system shown in Fig. 4 brings, therefore, the following advantages:

- a) The basic units of the system, i.e. the amplifier computers and longitudinal monitor have been designed to the rigid safety standards needed to meet the " 1×10^{-7} " requirements for automatic landing
- b) (a) is achieved using well known components and equipments which are familiar to service personnel
- c) As is shown in the accompanying diagrams, by the addition of units or sub-components already in use in the system, it is possible to provide duplication where required
- d) The system can be built up, progressively, to the various standards of all weather system described in Section 3

3. MAJOR STEPS TOWARDS FULL ALL WEATHER LANDING ON THE BAC ONE-ELEVEN

As was stated in the introduction, it is recognised on the BAC One-Eleven, that some operators will not wish to go as far as others on the all weather landing road, and there follows a brief description of the alternative standards being considered, some of which are firm projects and some of which are only under consideration.

Stage 1

Basic single PB20D autopilot with torque limit adaptor for soft pitch hardover characteristic as shown in Fig. 4.

Stage 2

'Split axis computer' Elliott/Bendix autopilot, with pitch monitor as shown in Fig. 4. This system is designed to be extended to autoflare or automatic landing.

Stage 3

A "fail soft" system as shown in Fig. 5. This is achieved by the addition of lateral monitoring to Stage 2.

Stage 4

A "fail soft" system with automatic throttle control (Fig. 6) either controlled from air speed and pitch signals, or from angle of attack plus acceleration such as SCAT provides.

Stage 5

A "single channel" autoflare system as represented by system No. 1 in Fig. 7 (with the second pitch axis servo not included) but with the automatic throttle system included. The situation display system could be utilised in this system.

Stage 6

The full automatic flareout system as shown in Fig. 7, with failure survival in pitch axis automatics, automatic throttle control, situation displays and the whole system being designed to meet the A.R.B. requirements of a 1×10^{-7} probability of a fatal incident for the critical phase of the approach, flareout and landing.

The expectation, in terms of reduced minima, from autoflare is the subject of considerable discussion. It is hoped that 100 ft. ceiling and of the order of 400 yds. R.V.R. is reasonable.

Experimental investigation of complete transition from I.F.R. to V.F.R. tends to show that this is not feasible with safety in weather conditions this poor. With autoflare, however, the transition is only in azimuth.

The pilot continues to be relieved of two of his three main tasks, i.e. control of pitch and speed, and can therefore be expected to handle the azimuth transition with safety at a low level. The level at which transition in azimuth will be carried out will be largely dictated by the quality of the localiser. If the localiser is such that it has good characteristics at all altitudes down to touch down, there appears to be no reason why the azimuth transition should not be left until somewhere near the flare commencement height. If on the other hand the localiser is poor it could be the limiting factor on break off height. Obviously the approach must be discontinued if the aircraft is still in cloud when the localiser becomes unusable. The situation display, giving a continuous picture of where the aircraft is relative to its manoeuvre limits on localiser, will certainly be of great value to the pilot in this situation.

Aircraft provisions

Provision for fitment of this stage, built into the aircraft can be offered at two levels: -

- a) Basic provision for autoflare consists of certain redesigned elements such as structure around radio altimeter aerial holes, provision for automatic throttle, etc., and is intended for operators whose probable intention is to incorporate autoflare when it becomes available and who wish to reduce the out of service time for installation
- b) Full provision for autoflare includes all structural and mechanical elements necessary for rapid fitment of autoflare when available. This provision reduces the out of service time for autoflare installation to a minimum.

N.B. These provisions, of course, only apply to customers who will take delivery before autoflare has completed its development and certification.

The full automatic flareout control system is the subject of the present firm development programme being jointly undertaken by BAC and Elliotts with Bendix support. The system, as in the case of the VC10, is based on the B.L.E.U. exponential flare law and as such does not utilise a glide slope extension scheme, but does include an attitude hold phase. This however, should be extremely short, as current developments in ground aids to I.C.A.O. Cat. II and III should enable glide slope coupling to be maintained to much lower altitudes. Similarly with the higher performance of the newer airborne equipment and improvements in failure warnings to be utilised in this system, it may well be possible to achieve coupling to lower altitudes on some Cat. I I.L.S. systems.

The automatic flare out system utilises a self monitored radio altimeter STR 51 developed for the VC10 system by Standard Telephone & Cables Ltd. It employs proven design techniques and components from other S.T.C. altimeters such as those used in B.L.E.U. systems, the altimeters used in the F.A.A. DC-7 aircraft etc. The altimeters give warning of passive, active, and "mal-performance" failures which is utilised to disconnect the system in use and for automatic changeover to the second automatic control system. This is done in the case of other system failure indications such as automatic pilot, glide slope receivers etc. There is one other aspect of this form of system which should be mentioned. The diagrams refer to monitored glide slope receivers. Similarly a schematic of a full automatic landing system of this type would refer to monitored localiser receivers. The term 'monitored' in this case means that the unit in question shall be capable of giving a warning of its own failure, that is failure to operate and, to as great a degree as possible, failure to function correctly. A glide slope receiver has been developed by Messrs. Marconi for the VC10 system, which provides such a warning, as does the S.T.C. radio altimeter. The technique does not necessarily mean a greatly complicated design. Indeed in the case of the glide slope receiver the solution is extremely simple.

Discussions are in progress with other radio manufacturers as to how the present receivers to the latest A.R.I.N.C. characteristic stand with respect to the requirement above, and what changes are necessary. It is emphasised that such an improved warning arrangement has general application apart from lower minima operation, providing the pilot with absolute indication of a unit's failure.

Summarising the autoflare concept described above, it can be said that BAC regard this system as a safe means of achieving the I.A.T.A. Phase II aims, which also contains the development potential for extension further to a Phase III full all weather landing system.

Stage 7

Automatic landing. Additions to (6) which would be necessary to achieve full automatic landing would probably consist of a further monitored azimuth channel, two azimuth landing computers to generate the runway alignment commands, monitoring elements to localiser receivers and possibly some modifications to the situation display instruments. Such a system would be capable of eliminating any cloud base restriction, but may still be subject to a significant restriction on R.V.R. because of the roll-out problem. The capability of the situation display instrument in this role has yet to be established. Some modification to the situation display or an alternative instrument may well be required to cover the roll-out phase.

As an intermediate stage between full autoflare (6) and full automatic landing (7), some consideration is being given to the possibility of supplying the pilot with azimuth director commands during the final phase of the approach.

Such a system might consist of full autoflare (6) plus azimuth landing computers, localiser receiver monitoring elements and some form of head up azimuth director instrument - perhaps added to the situation display. The need to install a complete additional monitored azimuth control channel would be avoided.

4. EXPECTATION OF LOWER MINIMA FROM THE VARIOUS ALTERNATIVES

A feel for the potentialities of each alternative system described can perhaps best be obtained by first considering all the barriers to the use of lower minima that presently exist and deciding how many barriers can be eliminated by each possible system. The potentialities of each of the systems described in Section 3 is summarised in Table I.

CONCLUDING REMARKS

Development of bad weather landing systems on the BAC One-Eleven is currently in progress.

A specific project, which is quite firm, is the development and certification of a safe autoflare system employing redundancy of systems in pitch and "fail soft" techniques in azimuth, and using the basic B.L.E.U. manoeuvre. This system will be flight tested by BAC during 1965 and offered for airline use in 1966. In addition, the potentialities of systems both less and more extensive than this autoflare system are being explored, so that a flexible approach can be made to the potential operators of the aircraft.

BAC is convinced that the basic principles of the B.L.E.U. radio altimeter controlled exponential flare form a satisfactory basis for an all weather system. It is also convinced that a safety standard demonstrably as high and preferably higher than at present being achieved in low minima landings must be a prime consideration in the system designs. In considering the safety issue, however, it does not exclude the possibility that some benefit is obtainable in terms of lowered minima with systems which are not fully failure survival on automatics.

The chart given in Table I seeks to demonstrate that some obstacles to progress can be removed with, for example, a completely "fail soft" system. The difficulty lies in determining just what the return is for each additional item added to the system, and where to stop. This is only likely to be fully resolved after some in-service experience has been obtained on the first systems. The flexibility being designed into the BAC One-Eleven systems should enable it to provide economical and practical solutions for most operational environments.

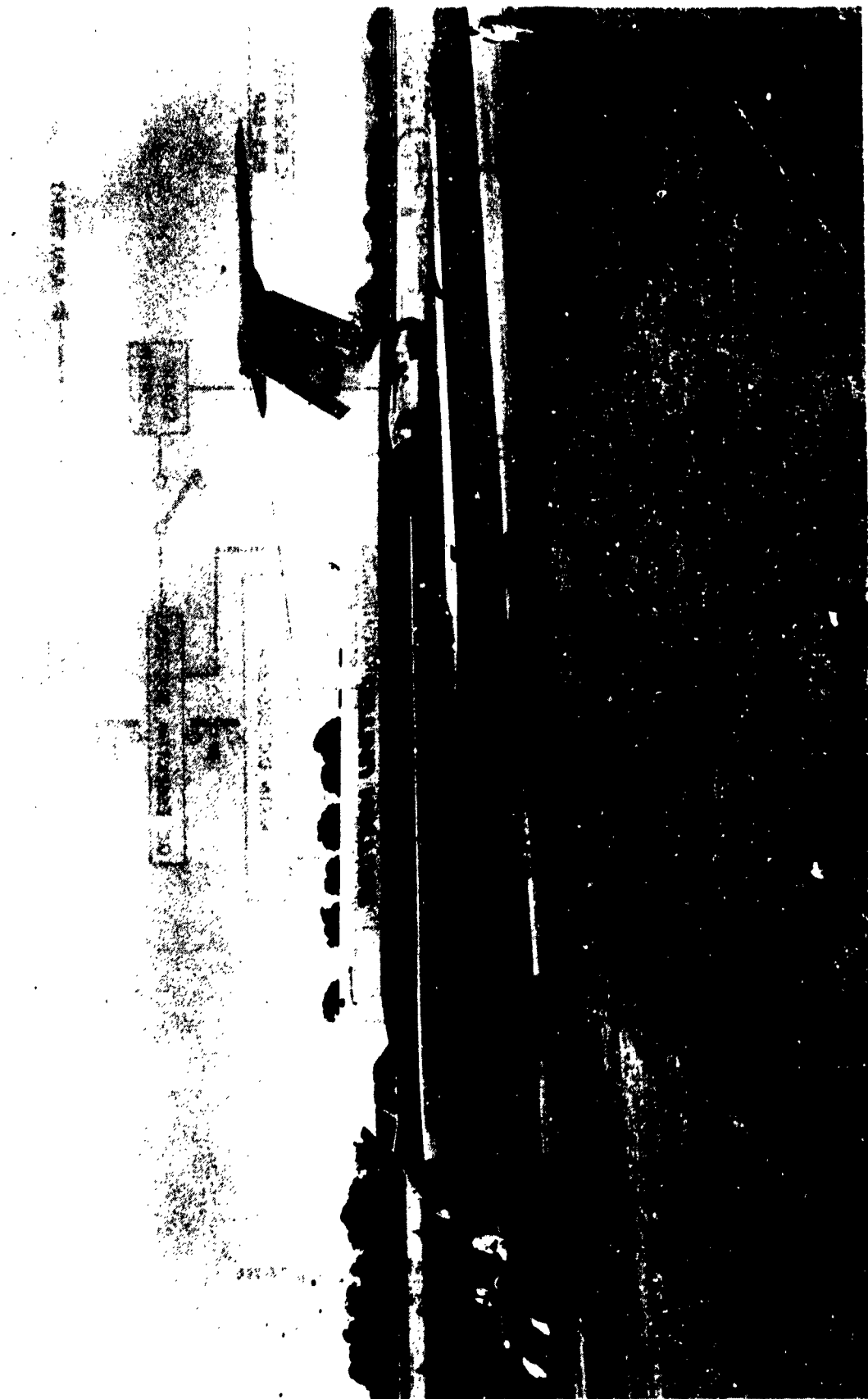
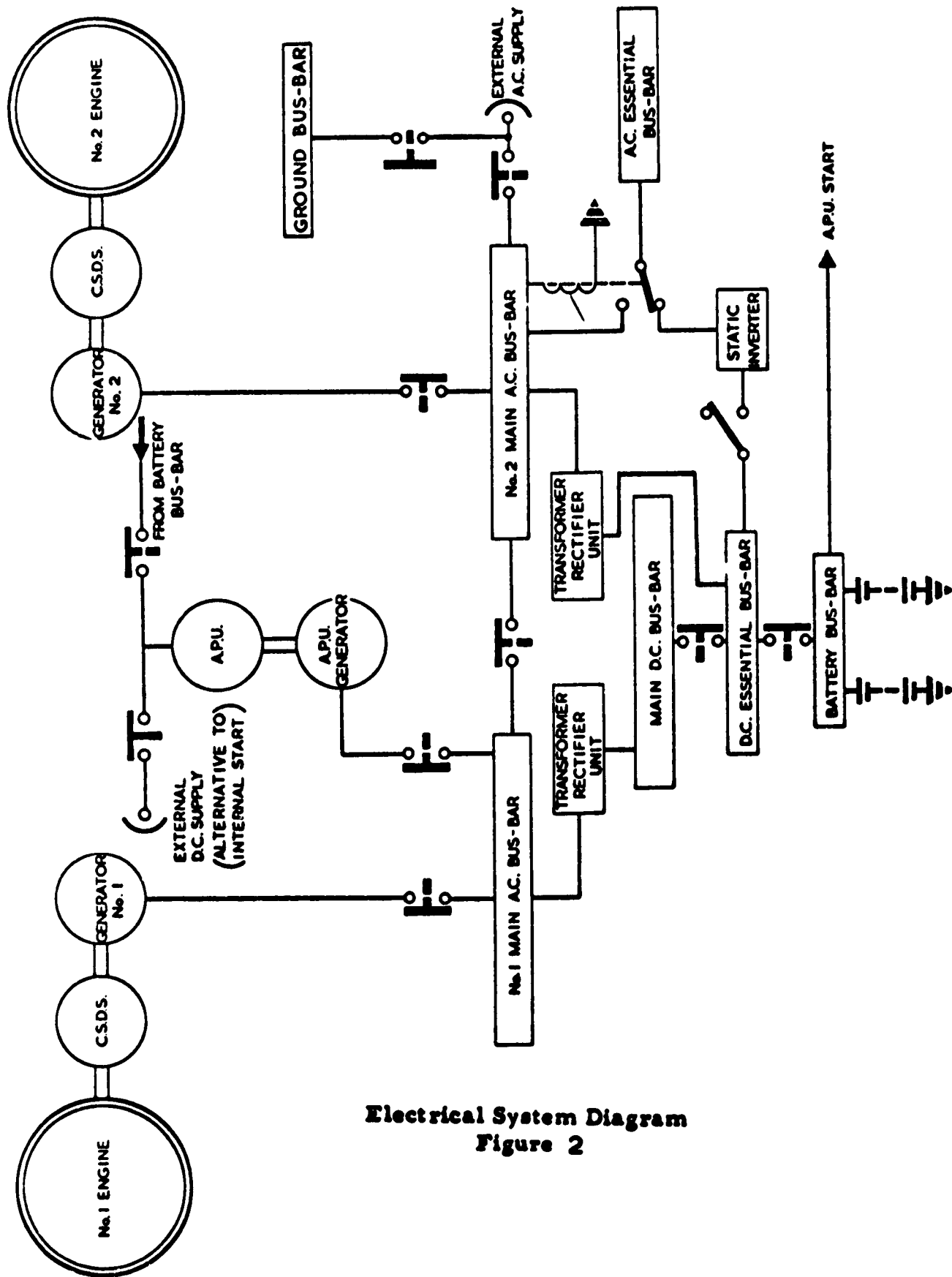


FIG.1



Electrical System Diagram
Figure 2

B.A.C. 1-11 AUTOPILOTS

FIG. 4. PROPOSED SPLIT AXIS COMPUTERS.

FIG. 3. STANDARD PB 20D.

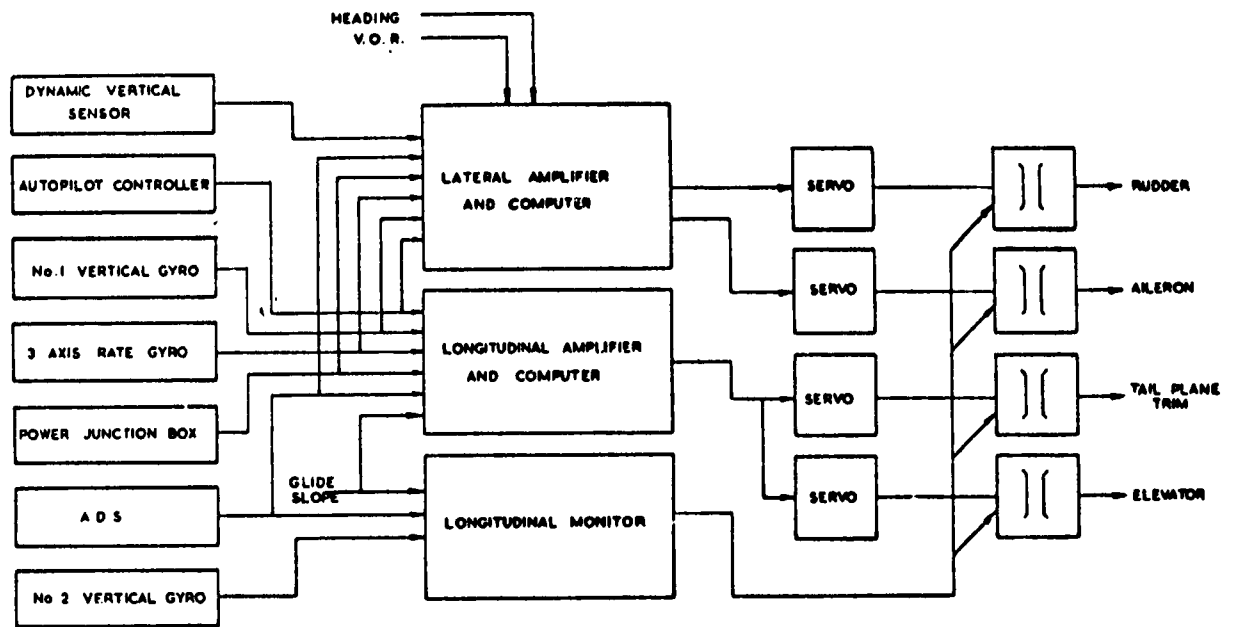
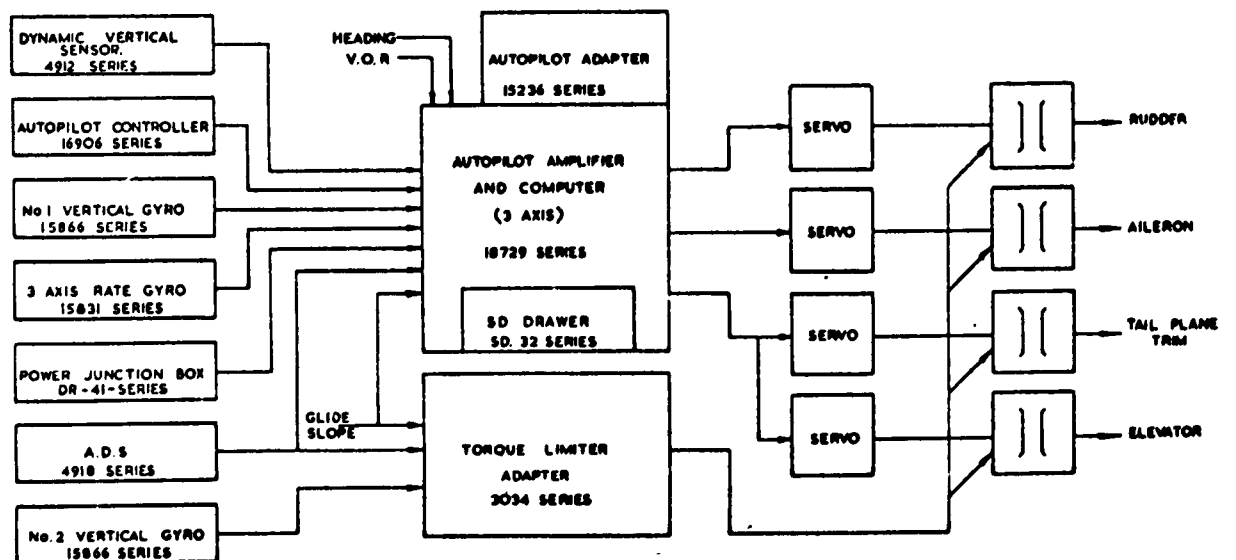


FIG. 4



BASIC SYSTEM CONVERTED TO COMPLETELY "FAIL SOFT" SYSTEM

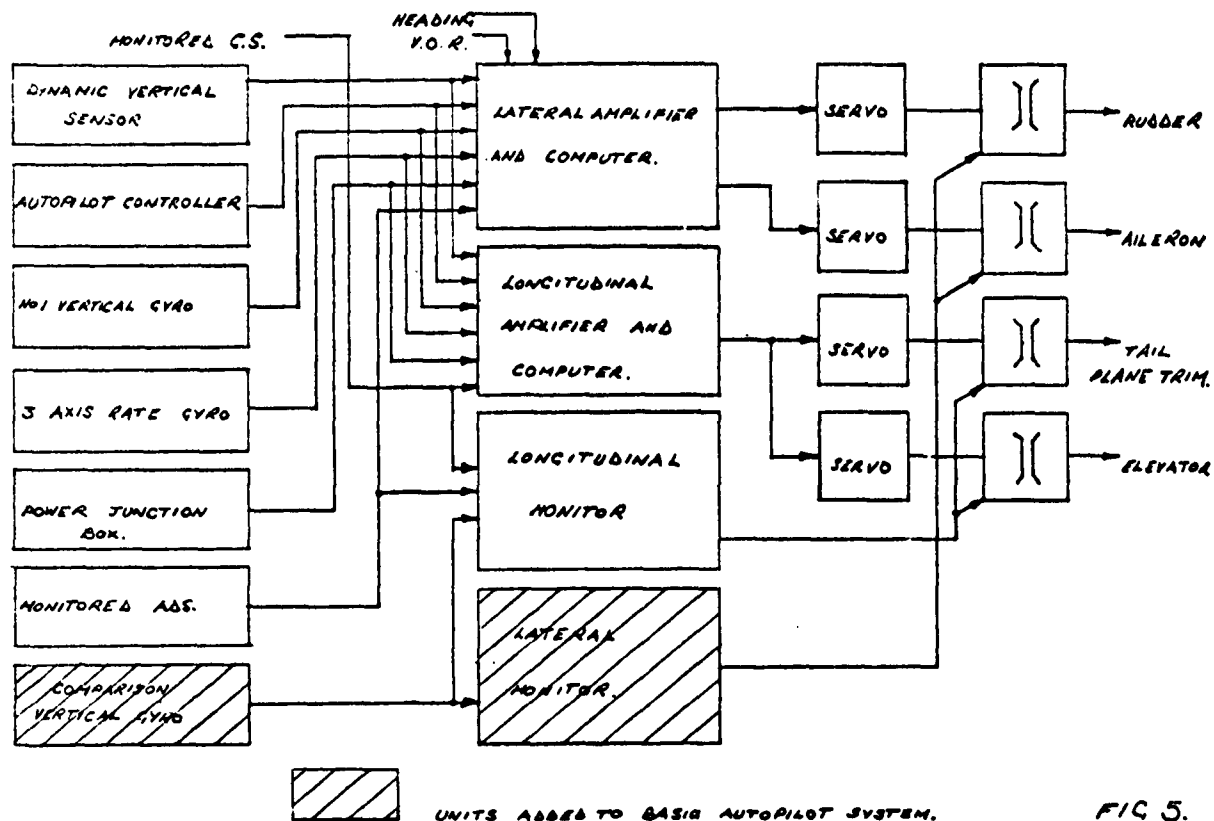
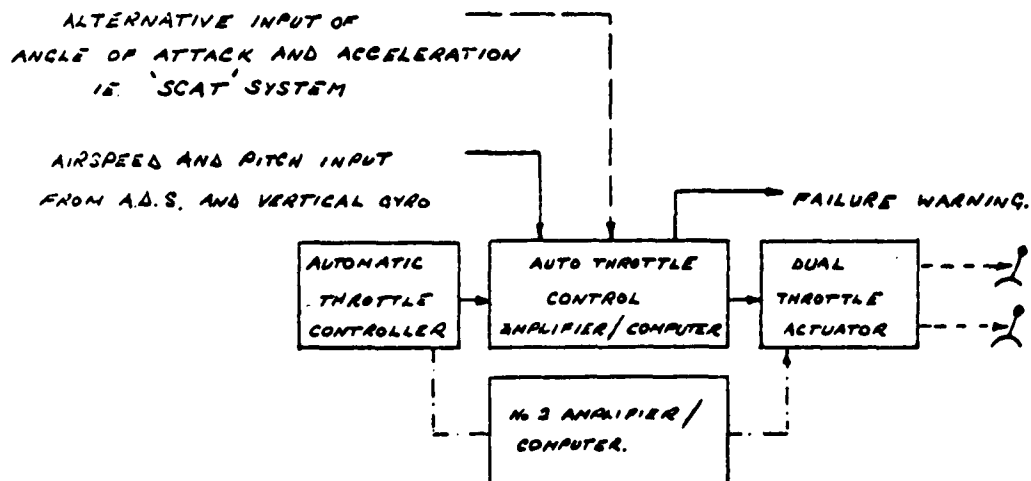


FIG 5.

AUTOMATIC THROTTLE CONTROL SYSTEM



NO. NO. 2 AMPLIFIER/COMPUTER MAY BE ADDED TO PROVIDE FAILURE SURVIVAL IN ELECTRONICS IF REQUIRED. (SYSTEM SEPARATELY PACKAGED FROM AUTOPILOT.)

FIG 6

BAC I-II PROPOSED AUTOFLARE SYSTEM USING 'SPLIT AXIS' AUTOPILOT.

No. 1 SYSTEM

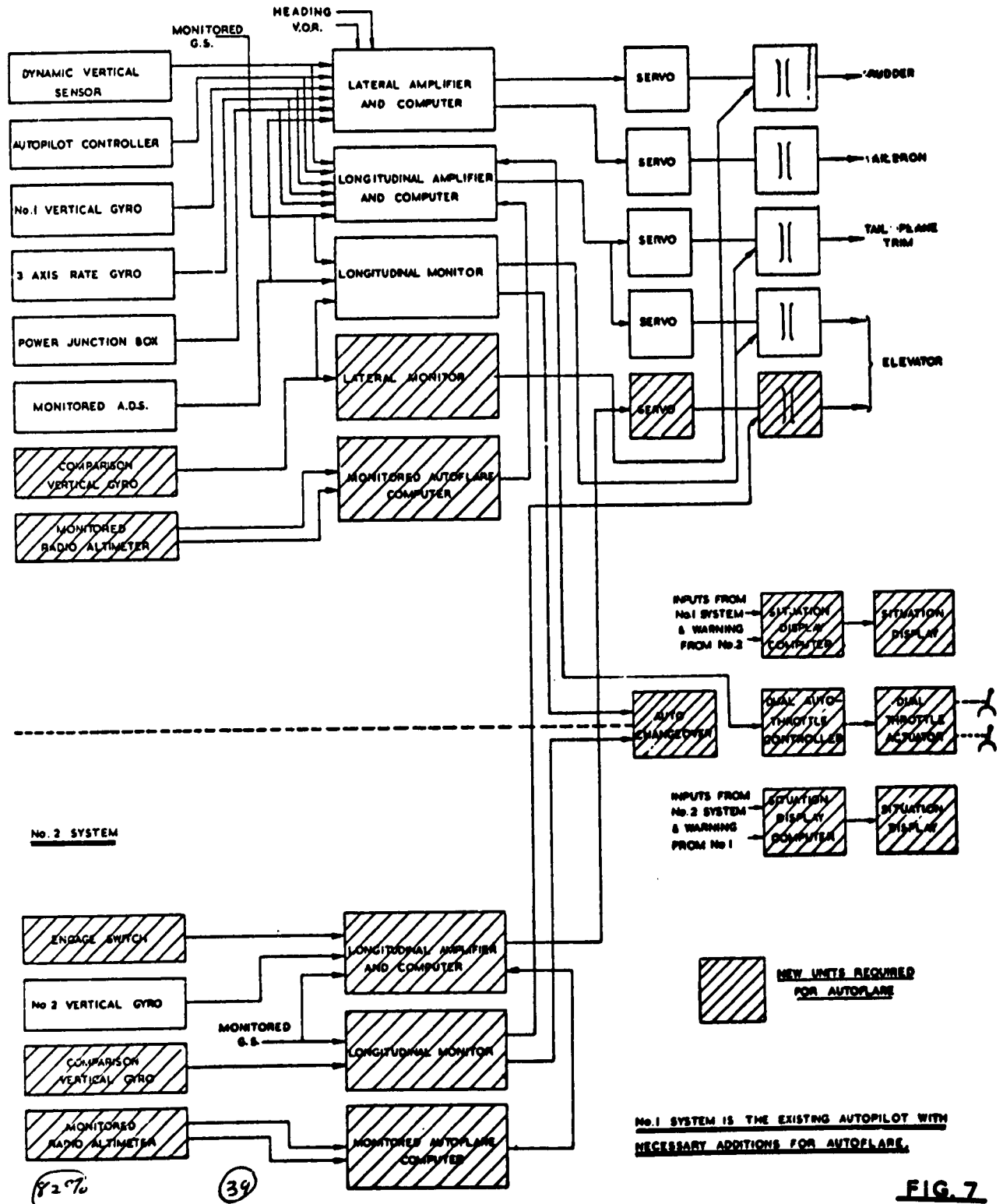
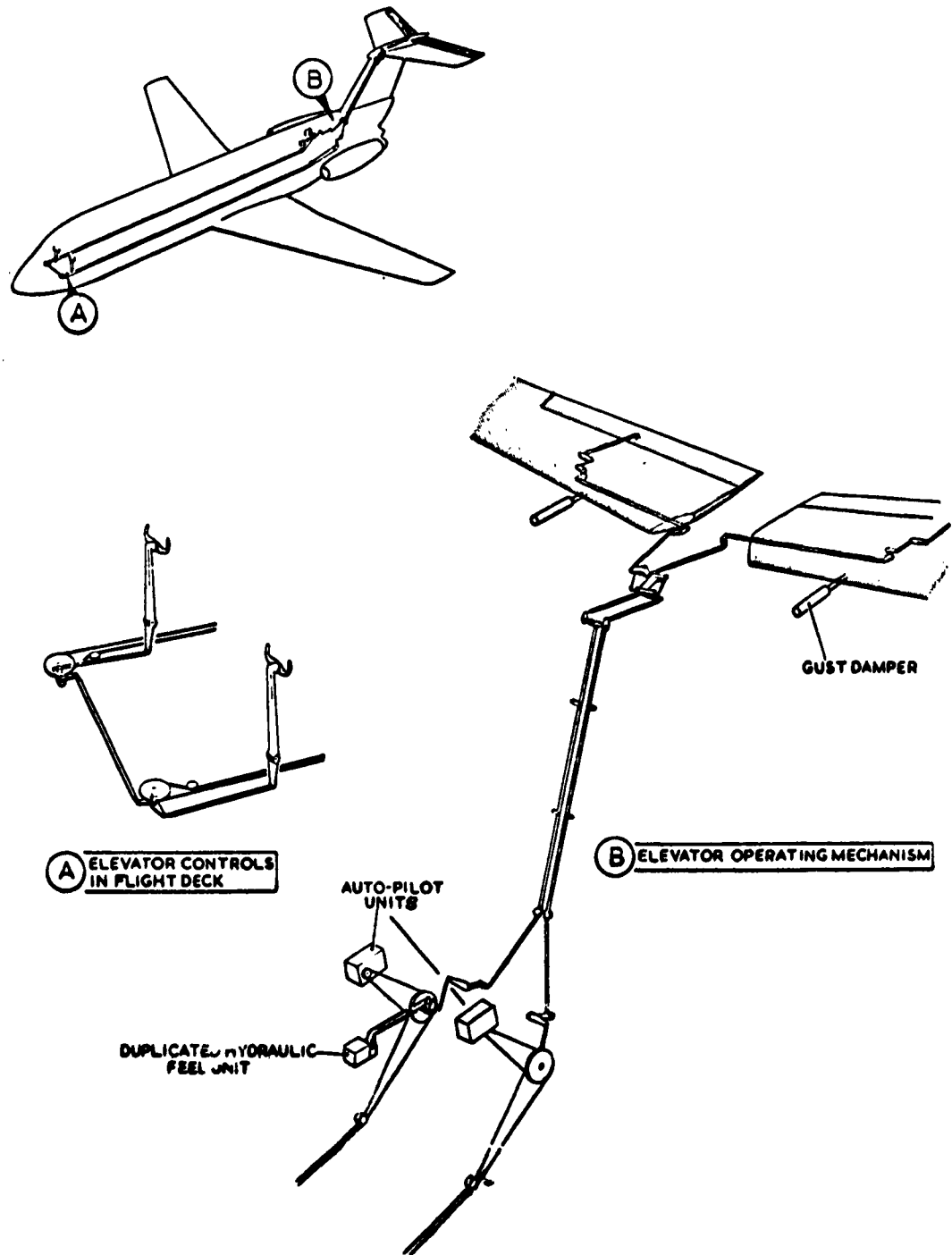


FIG. 7



Elevator Control

FIG. 8

TABLE I

POTENTIALITIES OF THE SYSTEMS FOR LOWERING MINIMA

BAC ONE-ELEVEN SYSTEM		Barriers to lower minima partially or completely removed by system											REMARKS
Test Ref. No.	DESCRIPTION	1	2	3	4	5	6	7	8	9	10	11	
		a b a b o d	a b o d	a b a b	a b a b	a b a b	a b a b	a b a b	a b o a b	a b o a b	a b o d e		
1	Radio Bendix R2000 autopilot, with soft pitch hardware characteristics	x									x x ? x x		Reduced certification break off height should be possible, relative to current systems.
2	Split axis computer Elliott/Bendix autopilot with pitch monitor	x									x x ? x x		- Ditto -
4	Fully fail soft autopilot with auto-throttle	x x x									x x ? x x		Further reduction may be possible.
	Fully fail soft single channel auto flare system	x x x									x x ? x x		
6	Full failure survival auto flare system	x x x x x									x x x x x		Significant reduction in minima. Phase II system.
8	All weather system with duplicate pitch automation and pilot participation in aimath	x x x x x ? x ? x x x									x x x x x x ?		
7	Full automatic landing	x x x x x x x x x x x									x x x x x x x ?		Phase III system

Barriers to the achievement of lower minima :-

1. Flight path disturbances due to autopilot hardware
 - 1a. Loss of height due to nose down runway
 - 1b. Bank angle and heading deviations
2. Sudden loss of automatic control and unmediated transition from auto to manual control
 - 2a. Complete loss of automatic control in pitch, aimath and air speed
 - 2b. Loss of pitch and aimath auto control
 - 2c. Loss of aimath only
 - 2d. Loss of pitch only
3. Height losses following decision to overshoot
4. Limitations due to glide slope characteristics
 - 4a. Poor low altitude localiser beam characteristics
 - 4b. Vulnerability to loss of glide slope signal due to ground station failure
5. Limitations due to localiser characteristics
 - 5a. Poor low altitude localiser beam characteristics including susceptibility to overlying aircraft effects
 - 5b. Vulnerability to loss of localiser signal due to ground station failure
6. Excessive pilot work: load causing deterioration in safety
7. Inadequate instrument aids for safe pilot management of the system
8. Lack of aircrew confidence in the system
 - 8a. Due to demanding nature of the task imposed on the system
 - 8b. Due to lack of adequate educational and training programmes
 - 8c. Due to inability to demonstrate system safety
9. Inadequacy of altitude information
 - 9a. Barometric altimeters - inaccuracies due to lag, position error variation with incidence and ground proximity, vulnerability to incorrect barometric setting, instrument errors, inherent lack of sensitivity
 - 9b. Radio altimeters - dependent on reasonable terrain characteristics under last phases of approach path
10. Aircraft characteristics unfavourable to lower minima :-
 - 10a. High approach speed
 - 10b. Poor cockpit view
 - 10c. Bad ground effect
 - 10d. Marginal lateral stability on approach
 - 10e. Unsuitable control circuits
11. Lack of roll-out guidance or control

THE FLIGHT DEVELOPMENT OF A
PRODUCTION AUTOMATIC LANDING SYSTEM

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at the

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1. INTRODUCTION

Smiths Aviation Division has been active in the all weather operations field since its first association with the Blind Landing Experimental Unit of R.A.E. in its autoland programme. The BLEU programme has been carried out using Smiths automatic pilots and associated systems, while the experience thus gained has been of great value in shaping the design of future Smiths equipment.

In the mid 1950s, Smiths electric automatic pilots of the SEP.2 series were in general service in a variety of transport aircraft. The company was also active in the flight instrument system field, and the Smiths Flight System was in service with a number of airlines. At the same time, a military autopilot from which many of the features of SEP.2 had been derived, was in production and destined for service with the R.A.F. V-Bomber force. It was against this background that the company decided to carry out a broad programme of research and development aimed at producing a new generation of autopilots and flight control systems suitable for all weather operation.

In 1957, a feasibility study led to the decisions to go for the development of a Multiplex automatic pilot. This conception has been described in greater detail elsewhere. Such a system can be used in the duplex form to provide a fail-soft characteristic, and in the triplex form to provide an autopilot which will survive a single failure. The feasibility study also led to certain decisions as to the scope of the operational features to be provided in an autopilot for the new generation of jet transports.

At this time, the SEP.2 was capable of flying jet aircraft, and the application to the Comet had confirmed this fact. Nevertheless, it was felt that the engineering implications of accepting the Multiplex principle were such as to make it desirable to develop a completely new system.

An experimental version of the new autopilot was built and a triplex pitch channel was subjected to a series of flight trials in a DC-3 belonging to the company's flying unit. This confirmed the feasibility of the Multiplex approach. At the same time, further development in conjunction with BLEU was resulting in a single channel automatic pilot capable of autoland, together with an efficient automatic throttle control system.

Towards the end of 1958, British European Airways decided that the Trident jet transports under development by de Havillands should ultimately be equipped for all-weather operation. My company was asked to undertake the development of a suitable system. It was felt that such an all-weather system should have the following characteristics:-

1. The automatic pilot, flight instrument system, automatic throttle control and basic flight instrumentation should all be integrated as a complete operational package.
2. In order to simplify the maintenance of this complex range of equipment, all the various systems would be developed in parallel using standard components and sub-assemblies where possible.
3. The safety studies inseparable from the development of this sort of systems would be extended to cover the complete package together with the aircraft power system and flying controls.
4. New procedures for line maintenance and trouble shooting would be developed on a system basis with the aim of facilitating trouble shooting within an aircraft turn round time of 30 minutes.

The development of this system was undertaken by Smiths Aviation Division as a private venture. However, it was apparent that a similar system would have wide application with Transport Command of the Royal Air Force, and for this reason the British Ministry of Aviation awarded a contract for the development of a similar military system.

It was decided to base the military system on that already under development for the civil application. It was also decided that this Government sponsored programme would include flight trials in two aircraft which would be specially converted as flight test vehicles. Finally, it was decided that the first specific application of the military system would be to the Short Belfast long range freighter at present under development for the R.A.F. This led to a subsidiary programme for the development of certain special navigation facilities for this aircraft.

Flight development work on earlier generations of Smiths autopilots and flight systems had been carried out in a variety of aircraft. The SEP.2 and SFS development was carried out in an Anson whilst the further development of military variants of the SEP.2 was undertaken in a DC-3. Subsequently, Varsity G-APAZ was provided by the Ministry of Supply as a flight development aircraft for the "First Generation" automatic landing system now in use in the Royal Air Force.

The Varsity had proved itself a reliable aircraft, and eminently suitable for this purpose. It has the nose wheel landing gear necessary for an automatic landing programme. The apparent limitations of low approach and landing speeds, piston engines etc. can really be considered advantages in the early stages of system development. The aircraft is reliable, has no vices and its handling by the pilot is straightforward.

This means that for work close to the ground, the flight crew are thoroughly familiar with the characteristics of the aircraft and can devote their attention to the flight control system and its development problems. Accordingly, a second Varsity, G-ARFP, was allocated by the Ministry of Aviation for the development of the new system.

The other aircraft allocated for the development programme was a Comet IIE, G-AMXK. This aircraft had previously been used by B.O.A.C. for route familiarisation and for the proving of Avon engines prior to the introduction into service of the Comet 4. Although the Varsity was obviously the less expensive vehicle in which to carry out a large number of automatic landings, the Comet was ideal for the evaluation of performance in the high speed, high altitude operating regimes. It was also suitable for investigating the handling of the system in low weather minima in conjunction with other operational problems characteristic of the jet.

The Varsity conversion was carried out by the Department of Flight of the College of Aeronautics, Cranfield. The conversion was completed in time for the aircraft to fly in the late summer of 1962. The Comet conversion was carried out in a series of stages by the de Havilland Aircraft Company, and flying began in 1960. Phase I was an investigation of the high speed, high altitude performance of an experimental single channel autopilot using the control laws which were to be used ultimately in the SEP.5 multiplex system. In the second phase, phase 1A, the aircraft carried a pre-production multiplex autopilot with duplex pitch, and simplex roll channels. A duplex yaw damper channel was also fitted. This phase cleared the basic performance of the multiplex autopilot, although no attempt was made to extend its operation to automatic landing. An essential feature of these two early phases was that the equipment was installed in the aircraft in such a way as to minimise the amount of conversion work required. In a later part of this paper, there is a description of the conversion carried out for phase 2 of the operation, involving more radical modifications of the basic aircraft, radio and electrical systems.

The work carried out on these two trials aircraft has provided a great deal of information on the problems to be anticipated when an integrated all-weather system is fitted retrospectively to a civil aircraft. Parallel experience of an installation designed from its inception for all-weather operation has been gained with the de Havilland Trident, in which a production system has now been flying for over a year. Finally, design studies were carried out as a result of which it was found possible to devise means of installing the equipment in a Caravelle.

At the present time, the Varsity has carried out its first automatic landings and is now committed to an intensive flight development programme. The Comet conversion for phase 2 of the operation has been completed and the aircraft has been rolled out. The Trident system has been worked up to a point at which approaches are being made to low altitudes using the automatics, the automatic throttle control, and the Para-Visual Director system.

2. SCOPE OF THE MULTIPLEX FLIGHT CONTROL SYSTEM

A schematic of the complete flight control system is shown in fig. 1. The complete system consists of the following sub-systems.

2.1 SEP.5 Multiplex Automatic Pilot

In the Varsity this system consists of pitch and roll axes which can be operated at triplex level, with a rudder axis at duplex level.

In the Comet, the pitch and roll channels are similar to those fitted to the Varsity but the rudder channel is essentially a duplex yaw damper system. This means that in normal cruising flight under either manual or automatic control, automatic inputs to the rudder circuit are injected through actuators operating in series with the rudder pedals, which do not move. In the approach and landing configuration separate servomotors are clutched in to provide a duplex rudder channel facility with the high authority necessary to remove the drift during an automatic landing.

2.2 Attitude System

In both aircraft three vertical gyro references are carried. Two are used to feed the pilots and co-pilots attitude displays, the third being used to feed the flight director system.

2.3 Compass System

Both aircraft carry twin gyro magnetic compass systems integrated with the situation display element of the flight system.

2.4 Air Data System

Each aircraft is equipped with twin air data computers. Apart from operating the basic pilot's manometric instruments, these are used to supply a variety of manometric information to the autopilot and flight instrument system.

2.5 Flight Director System

One feature of the operational requirement is that it calls for a flight director system duplicating all the facilities available through the automatic pilot. Compensatory type director bars are displayed on the attitude indicators and the director functions are selected simultaneously with those of the autopilot on a common Flight Controller.

2.6 Automatic Throttle Control

The automatic throttle control system uses airspeed signals generated by the twin air data systems in conjunction with pitch rate derived from the autopilot. The basic system is familiar to those with knowledge of the FAA DC-7 installation, although the actual equipment is of a later generation, the complete system being contained in a $\frac{1}{2}$ short ATR box.

2.7 Operational Facilities

The complete system provides a range of operational facilities covering all phases of flight up to and including landing. The following is a brief summary of the facilities available:-

Autopilot and flight director, attitude, I.A.S, Mach, height and rate of descent locks.

Automatic or flight director acquisition of a pre-selected cruising altitude following a climb or descent on any of the above locks.

Automatic VOR, Doppler and Tacan coupling.

Automatic and flight director ILS approach to a low altitude including automatic control of the airspeed through the throttles.

Automatic landing including both flare and decrab elements, with the ability to use any form of split axis control at the pilot's option.

3. A REVIEW OF SOME PRACTICAL ENGINEERING PROBLEMS

3.1 System Safety

As a result of previous experience with similar projects, it was felt that a very clearly defined safety philosophy should be formulated at an early stage in the project. The practical engineering difficulties of implementing any safety philosophy are considerable, and can only be overcome if it is always possible to relate specific detailed engineering problems to some overriding operational philosophy. This is particularly so where redundancy in any form is used to achieve safety. Without an overall systems study in the early stages of the project, it is possible to over complicate the detailed design in ways which are not operationally necessary.

The basic conception of the system is that the primary means of landing the aircraft in zero-zero conditions is through the use of the automatic pilot. The triplex pitch and roll channels are so designed that failures in one axis will not affect the other, while the loss of a single sub-channel leads to an automatic reversion to the duplex mode without risk of the channel cutting out.

Duplex redundancy only is used in the rudder channel, where it is felt that an automatic disengagement of that axis is unlikely to hazard the aircraft, provided that it occurs passively.

The air data and compass system, both of which provide basic flight information, are duplicated. Here the safety philosophy states that it should be impossible for a failure in one system to be communicated to the other, while pilot warning of a failure can be secured by comparing the outputs of the two systems.

The function of the flight director is two-fold. In cruising flight, certain autopilot functions associated with locking to heights, airspeeds etc. are not duplicated, and a single failure can lose a particular facility. However, all these locking facilities are duplicated in the flight director system which is thus available as a back up should an autopilot facility be lost. Accordingly here the philosophy is to drive the autopilot and flight director systems from separate systems and separate power supplies, ensuring that no common failure can affect both systems.

In the case of the automatic throttle control, it was felt that the system need not be given the ability to survive a failure. Manual operation of the throttles to hold the airspeed is feasible, and the pilot can be given an indication of the correct height at which to close the throttles during automatic landing. However, it is important that a hardover of the throttle system should not hazard the aircraft by producing a large airspeed excursion, particularly at low altitudes. Accordingly, the auto-throttle system uses two separate airspeed inputs derived from the air data computers together with a pattern of redundancy aimed at comparing throttle positions to cut the system out in the event of a hardover. It has been found feasible to limit the consequences of a failure of the integrator, pitch rate or flap position terms, and these are not duplicated.

3.2 Fault Analysis

With the above philosophy as a point of departure, it was decided to set up a special fault analysis team within the system development organisation. The procedure adopted for fault analysis was described in a recent paper submitted to the I.A.T.A. Conference at Lucerne. Broadly speaking it consists of surveying the whole system and determining areas within which it is vulnerable to failures.

One example of a vulnerable area arises when it is necessary to use more than one of the system power supplies within a particular electronic unit. The complete system is normally driven from three separate supplies. The design is such that its operation is not affected by differences of phase, frequency or volts between the supplies provided that they remain within normal limitations. However, at some points it is necessary to bring systems together, for example where the sub-channels of a multiplex autopilot are equalised. Under these circumstances, proper isolation must be preserved between the system signal circuits themselves and the separate power supplies if these are also required within the one unit. The aim of the fault analysis is to investigate the effect of all possible failures, for example, short circuits or open circuits, and to determine where special circuit segregation measures are necessary within units. It has been found necessary to make this a continuous activity, with the results of the fault analysis being fed into the detailed design of the hardware, the test procedures, and ultimately the overhaul requirements.

Fig. 2 shows part of a typical electronic assembly. The design is such that segregation is maintained between two circuits as a result of the fault analysis requirement.

3.3 Aircraft Installation Requirements

It has been shown that the flight control system itself has been designed to very high standards of safety and reliability. However, the system cannot by itself give a particular aircraft the necessary standard of safety required for automatic landing. All other aircraft systems which are directly concerned with controlled flight of the aircraft must be designed to similar standards. This includes powered flying controls, engine controls etc.

Some account must also be taken of other systems (e.g. electrical generation and distribution) which, although not directly connected to the aircraft controls would result in a catastrophic failure of the aircraft if a fault developed and had repercussions in the other vital systems. These considerations are now routine in the design of a new aircraft but to apply them retrospectively to present day standards to the trials aircraft presented many problems. It was decided that some effort had to be made to do this in the interests of proving the complete system philosophy and in order to secure a high standard of safety in aircraft which would be operated in zero-zero conditions.

A requirement for the Varsity was that the aircraft should not exceed a specific maximum all up weight required for operation from the short runways at the company's home airfield at Staverton. This figure was below the maximum all up weight for the aircraft. The minimum operating crew was to be two pilots and thus the management of all systems had to be possible from either the first or second pilot's positions. In this aircraft the biggest problem was that of providing an electrical system to a standard comparable with that of the flight control system. The assumption was that a complete loss of electrical power in the aircraft could cause disaster if it occurred in close proximity to the ground while carrying out an automatic landing in zero-zero conditions. In addition, it was required that no single fault condition could cause the loss of more than one power supply to the flight control system. The aircraft conversion was to be to the satisfaction of the Air Registration Board and a Certificate of Airworthiness in the Special Category was required to enable its operation as a civil aircraft by the company's flying unit.

It was decided that the electrical and radio systems in the Comet would have to be completely rewired using the segregation principles accepted for the flight control system. Three completely segregated electrical generating and distribution systems were to be provided.

The Comet radio installation to the original B.O.A.C. standard was inadequate for all-weather operation. The final radio installation represents a combination of the all-weather requirement and of certain particular operational requirements involving the use of both civil and military airfields. The complete installation comprises the following:-

- 3 VHF Communication Transmitter/Receivers
- 1 UHF Communication Transmitter/Receivers
- 2 HF Communication Transmitter/Receivers
- 2 ADF Receivers
- 2 ILS/VOR Navigation Receivers
- 3 Leader Cable Receivers
- 3 Radio Altimeters
- 2 Marker Receivers
- 1 Doppler Installation
- 1 Tacan Receiver
- 1 Weather Radar

The Leader Cable, UHF, Doppler and Tacan installations reflect the requirement to operate through military airfields and the needs of a special navigation system.

The Varsity flying controls are conventional, the surfaces being operated by direct manual control. The integration of the autopilot with the flying controls was along the lines suitable for general retrofit to present day aircraft.

In each axis of control a special servomotor mounting is provided to which can be attached up to three completely self contained servomotors, each driven from a separate sub-channel. Included in each servomotor is an electro-magnetic clutch and a torque limiter. In the event of a hardover developing in one sub-channel of the system, that particular servomotor develops a high output torque which is opposed and held by the two remaining servomotors until it reaches a pre-determined value. At this value the torque limiter switch in the servomotor assembly operates to disengage the faulty sub-channel.

Each sub-channel in the system is capable of flying the aircraft unaided. This is an intrinsic feature of the multiplex system but also permits the autopilot to be used in an emergency single channel reversionary mode following failures, with conventional protection against a hardover.

The consequence of this requirement is that each individual servomotor can develop sufficient torque to fly the aircraft, the maximum torque potential of the system being thus three times that required for adequate control. In order to guard against the

possibility of the autopilot overstressing the control runs, a torque authority limitation device is provided within the servomotor mounting. This provides three segregated outputs which limit the torque imposed by the three servo sub-channels. This authority limiter is also used to provide conventional protection against a hardover when an axis of control is used at simplex or single channel level. The triplex servomotor assembly is shown in fig. 3.

Although the Comet is equipped with fully powered controls, no effort was made to integrate the autopilot actuators with the hydraulics. This is also true of the Hawker Siddeley Trident, where it has been found possible to achieve the necessary standard of autopilot performance using a conventional servo arrangement. The servomotor installation is therefore similar to that on the Varsity, although control surface limit switches and 'g' switches are used in the emergency single channel reversionary mode. In practice, this mode of operation is a useful answer to the problem of maintaining a system which includes redundancy. The operator can if necessary operate the aircraft under automatic control following failures, arranging to carry out remedial action at a main base.

4. VARSITY INSTALLATION

Fig. 4 shows this aircraft. In its original form it was fitted with ventral blister for its role as a navigation trainer. This was removed in the interests of weight saving. A dual braking system incorporating Maxaret control was installed. The interior was completely remodelled and the racks shown in fig. 5 were installed to take the electronic equipment.

A special station for a flight test engineer was installed in the position normally occupied by the jump seat in a civil aircraft. Seating for five other persons is provided in the nose of the aircraft in order to allow the system to be demonstrated.

The existing instrument panels were removed and a completely new one piece panel designed and fitted. This is shown in fig. 6. Fig. 7 shows five completely new cockpit roof panels which were fitted, that in the centre containing the switches and indicators for the management of the electrical system. The radio controllers are fitted in the roof and the panel immediately above the windscreen holds the propellor controls. The port panel contains engine starting and airframe de-icing controls, that on the starboard side carrying some of the engine services.

Following the practice in the Hawker Siddeley Trident, all the basic aircraft system warnings relating to engines, fuel, de-icing etc. were rationalised and incorporated together with the electrical and flight control system warnings in a comprehensive centralised warning panel. This is a two stage red and amber system with flashing lights. The warning display panel is in the centre of the cockpit glare shield.

The triplex flight control system requires three separate sources of a.c. power. The basic generation system on the aircraft was a 28 volt d.c. system. A new power system was designed and rig tested to prove that single faults on the d.c. system would have no unacceptable secondary effects on the three a.c. supplies.

The basic d.c. power is obtained from four engine driven generators giving a total generator capacity of 24 kilowatts, double the output of the original Varsity installation. Four 2.5 kva invertors are installed and these give ample power to cope with any future increases in demand. Experience has shown that this is a characteristic of research aircraft on which additional flight test instrumentation may be required or new experimental systems installed.

Fig. 8 shows the distribution system including the busbar boxes, circuit breakers, contractors and relays. The various illustrations show the way in which the aircraft cables are carried in ducts. Separate ducting is used for the three separate power systems and the separate elements of the flight control system. In the illustrations the covers over the ducts have been removed to make this segregation visible. Fig. 9 shows the flight test engineers station including the flight systems panel which is used in the air to check that all the available system redundancy is functioning. It is also used for certain ground checks and to enable the crew to select a lower level of autopilot redundancy should they desire to. The system is capable of operating from either localiser or leader cable guidance and the controls of the latter are included at the engineers station. At least 50% of the racking area in the cabin is occupied by flight test instrumentation. Means are provided to vary a large number of parameters in the various systems, these normally being set to optimum values by parameter boxes plugged into the front faces of the ATR racked units. The racking also carries trace recorders and the other recording equipment referred to later in this paper.

5. COMET INSTALLATION

For the first two phases of the Comet trials, the existing aircraft flight system electrical and radio installations were retained. The subsequent phase, phase 2, includes trials of a Multiplex autopilot together with the other associated systems described earlier in this

paper. It was decided to engineer the complete installation to permit automatic landings to be carried out in genuine bad weather conditions with a high level of safety and reliability. The conversion work for this purpose was spread over a period of twelve months.

The aircraft had earlier been used for engine development work, and two different types of engines are installed. The outboard engines are Avon RA29s, the subject of the original trials. The inner engines are the earlier Avon RA9 engines. It was found that larger alternators could be fitted to the RA29 than to the RA9 engine, and each of the outer engines can also provide 400 amps of rectified 28 volt d.c. 200 amps is available from each of the alternators fitted to the inners. It was possible to use these facilities to provide three basic generating systems, each capable of giving 400 amps.

The alternators on the inner engines feed a common busbar through transformer/rectifier units. This is termed the WHITE system. Connected to this busbar are the main aircraft batteries and an emergency busbar which can be isolated and supported by batteries in the event of the rest of this WHITE generating system failing. The emergency busbar is used to feed fire warning circuits, emergency hydraulic pumps etc.

The port outer engine supplies a second d.c. power system, designated the BLUE system. The starboard outer supplies a third YELLOW electrical system. The three systems are completely segregated and individually regulated. There are no paralleling or equalising connections. Thus a single fault condition in one system cannot have a reflected effect on the other two. This is important in the event of, say, a major earth fault. Under these conditions transients imposed on healthy parts of the system can exceed those normally anticipated, both in magnitude and duration as protective devices may take a relatively long time to clear. This is a result of the need to provide adequate system stability to cope with normal switching transients etc.

A.c. supplies for the flight control system are derived from three separate 3 kva invertors. One machine is supplied from each of the BLUE, YELLOW, and WHITE 28 volt d.c. busbars. The invertor outputs are 115 volt 3 phase 3 wire at 400 c.p.s. The aircraft for which the new flight control system has been designed have 200 volt 3 phase 4 wire a.c. generating systems, and transformers are provided to produce this supply. As a result of the above arrangement, it is possible to use airborne equipments operating on either 115 volt or 200 volt a.c. supplies, a useful asset in a development aircraft which may have to accept a variety of equipments.

Reference has already been made (see Section 3.3) to the scale of radio carried in this aircraft. Fig. 10 shows part of the aerial installation.

The cockpit space in the Comet is limited, particularly behind the instrument panels. Nevertheless it has been possible to make a very clean installation and this is shown in fig. 11. Fig. 12 is a close up view of the instrument panels. It will be seen that the Flight Controller for the complete system is mounted vertically in the centre of the panel. This is not standard practice, the unit having been designed to be built into a centre console between the two pilots. By mounting the unit in the manner shown, it is possible to avoid anything but minor modifications to the throttle pedestal and its controls. The cut-out buttons for the automatic throttle control system can be seen on the outboard sides of the outer throttle levers. The three indicators above the Flight Controller are Landing Indicators, displaying the outputs from the three Radio Altimeters. Information on flight system failure is conveyed to the pilot through the indicator panels mounted above the horizon displays.

The crew stations on the left of the flight deck are designed to be occupied by the flight trials engineer controlling the test instrumentation and a second flight trials engineer or a navigator.

Fig. 13 shows the main cabin. The electronic equipment is carried in three racks with all the interconnections brought out in junction boxes. This has been found a useful feature in other research aircraft in which it is often necessary to make rapid system modifications or to connect up for special instrumentation requirements. Fig. 14 shows the instrumentation console from which all the recording facilities can be controlled by a flight trials engineer.

6. FLIGHT TRIALS INSTRUMENTATION

It has been found necessary to design a range of equipment specially suited to the requirements of a flight control system development programme. Photographic trace records have been found best for this type of work and suitable recorders and galvanometers are easily available. It is however, necessary to provide equipment to convert a wide variety of electrical signals, both a.c. and d.c. to a form suitable for feeding the galvanometers. As well as the usual problems associated with correct sensitivity levels, demodulation, amplification and loading, the integrity of the flight control system has to be preserved when signals internal to it are brought out for recording purposes. Thus it has been necessary to maintain the segregation standards in this instrumentation. As four invertors are used in the aircraft, it is necessary to provide for the possible use of 24 phase references for demodulation purposes.

In order to enable maximum utilisation of flying time to be made, it is a requirement that it be possible to cater for different tests during one flight. Obviously, the changes associated with a change in tests have to be kept to a minimum and must be capable of being carried out quickly by the operation of switches. It is also desirable to be able to revert to any particular instrumentation set up without laborious re-calibration.

The standard equipment includes three types of input unit (high and low impedance d.c. and a.c.) to process the signals to be recorded and a unit (power pack and calibration unit) to provide the necessary electrical supplies and calibration voltages. The complete instrumentation system is sub-divided into a relatively large number of units or modules and the method of interconnection used gives great flexibility. The system can record signals originating from the flight control system, aircraft control surface position pick-offs, or sensors used to detect the aircraft actual behaviour. These may include independent gyros, airspeed sensors etc. if required.

Two photographic trace recorders are used, each of which is fitted with 25 recording galvanometers. In addition, two signal units giving blip indications and two datum units are fitted. Time indication is given by printing full width lines on the 6" recording paper.

A central time control unit has been designed to give a wide range of timing pulses for simultaneous use in both recorders. Pulses at minute intervals are used to operate synchronised counters which print numbers on the trace records whilst a similar counter repeats the information at the control panel at the flight test engineer's station.

A two track tape recorder is provided on which normal intercomm conversations can be recorded. The second track is available for independent use by the flight test engineer.

The above description relates primarily to the recording installation in the Varisty. However, the Comet installation is somewhat similar and the same basic modules are used in it. This has simplified the maintenance of the recording equipment. Similar recording techniques are used in other aircraft involved in the development of the SEP.5 multiplex autopilot. A central library of flight trials recordings has been established with a cross referencing system which enables any particular aircraft problem to be analysed using data available from all the flight test vehicles.

7. FLIGHT TRIALS TECHNIQUES

With the instrumentation system described above, it is possible to record a variety of autopilot parameters such as gyro signals or computed data as it appears at various points in the signal chain. In addition, the trials aircraft are fitted with pick-offs enabling surface positions to be recorded.

During intensive autolandings evaluations such as those carried out by BLEU, the actual flight path of the aircraft in the approach and landing can be recorded by kinetheodolites. By using suitable means of cross referencing the data gathered on the ground and in the air, it is possible to examine the landing performance in very great detail. This has been done in the past and the techniques developed as a result of the earlier work will be extended to the intensive phases of the flight test work on the two new aircraft.

However, an important aspect of the development of any all-weather system is its evaluation at a variety of airfields under a variety of weather conditions. Obviously, the signals present within the aircraft can still be recorded adequately, but there are difficulties in obtaining an accurate record of the aircraft's flight path at airfields which are not fitted with the necessary ground installations. Present studies are aimed at perfecting an inexpensive and simple technique to obtain photographic recordings using a commercial type cine camera. Apart from its value in recording the very large number of landings to be made during the development programme, such a technique has obvious applications once the new systems go into airline service.

The ultimate clearance of the multiplex autolandings autopilot rests on the fact that it can be shown to perform within certain defined limits over a certain range of wind and weather conditions. It is expected that the equipment will first of all enter operational service by being used for landings in fair weather conditions. Approximately two year's operation of a fleet of from 25 to 50 aircraft can give sufficient reliability data to verify the assumptions as to system failure rate and the resultant chance of a malfunction during a landing. During this working up period, it will also be necessary to record as many landings as possible. It is hoped that a combination of a simple photographic technique with suitable pilot questionnaires will enable this to be done. Another possibility to be explored is that of using aircraft flight recorders to record information relevant to an automatic landing. Apart from the possible use of crash recorders following an incident, some airlines are considering the wider use of flight recording as an aid to monitoring the performance of the aircraft and its systems. Obviously any tendency in this direction should improve the chances of recording the success of an all-weather system.

Previous autoland trials have led to the evolution of crew techniques which are being extended to the work on the new system. It has always been normal practice to carry an operating crew of three, consisting of two pilots and a flight test observer. During an autoland, the latter monitors the overall performance of the system and calls out heights derived from the radio altimeters as the aircraft goes through the various phases of the flare and landing. Normally, the aircraft captain is occupied in looking ahead and is prepared to take over manually should this be necessary.

The autopilots used in this work sometimes employ quite high control forces and cannot necessarily be overridden manually in all axes. It has therefore always been felt that some special provision must be made to enable the pilot to override the system in an emergency.

These provisions include a new type of autopilot cut-out button and a system of manual override detectors. The cut out button includes a solenoid mechanism which ensures that a relatively heavy force is required to break it out while the autopilot is engaged. When the autopilot is disconnected the solenoid relaxes and the button requires a comparatively light force to operate it. This facility has two advantages. It discourages inadvertent disengagement of the autopilot by unconscious operation of the button and it gives the pilot a tactile means of knowing whether the autopilot is satisfactorily disconnected from the controls. The manual override detectors are mounted in the control runs at a point adjacent to the control column such that they detect the reaction when the pilot attempts to override the automatics by pushing against the servos. Should this push force exceed approximately 40 lbs. the autopilot disconnects. This system enables us to combine the advantages of a manual override facility with an autopilot having the high control authority and high operating torques necessary to accomplish accurate approaches in landings.

In most multiplex installations, it is the practice to have a high authority pitch trim system such that the aircraft will be virtually in trim should the automatics be disconnected during the latter stages of an approach and flare.

In optimising automatic landing autopilots a progressive approach is adopted. The autopilot is first of all cleared for low approaches so that its low speed performance is brought to the best possible operation. After that the automatic throttle control is optimised and finally the operation is extended to automatic flare and automatic landing.

8. ACKNOWLEDGEMENTS

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9. REFERENCE

1. C. M. Copage. "Principles of Fault Analysis Applicable to a Flight Control System", submitted to the International Air Transport Association Fifteenth Technical Conference, Lucerne, April 1963. R.I.D. 694, January 1963.

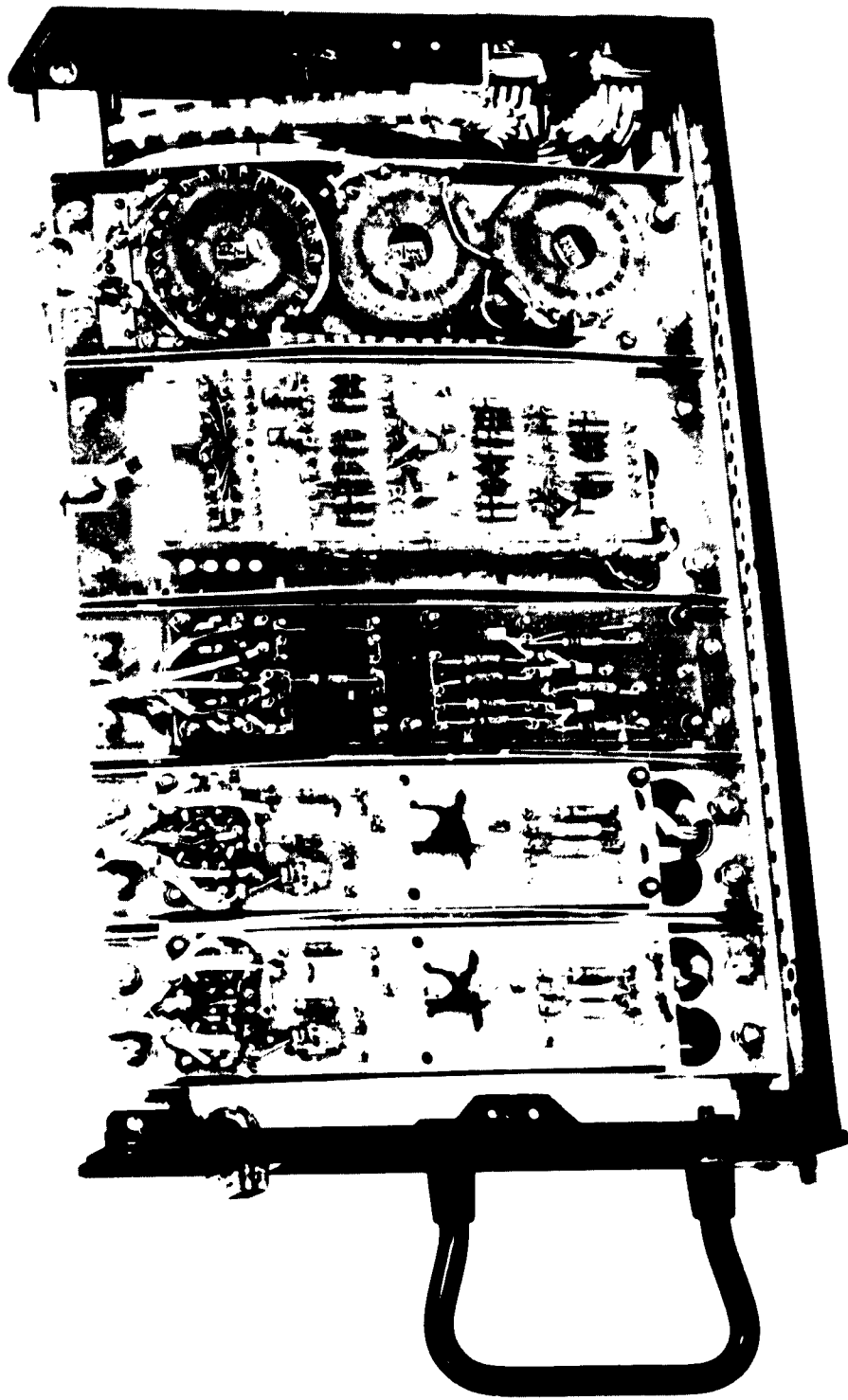


FIG. 2 GLIDE SLOPE COMPARATOR

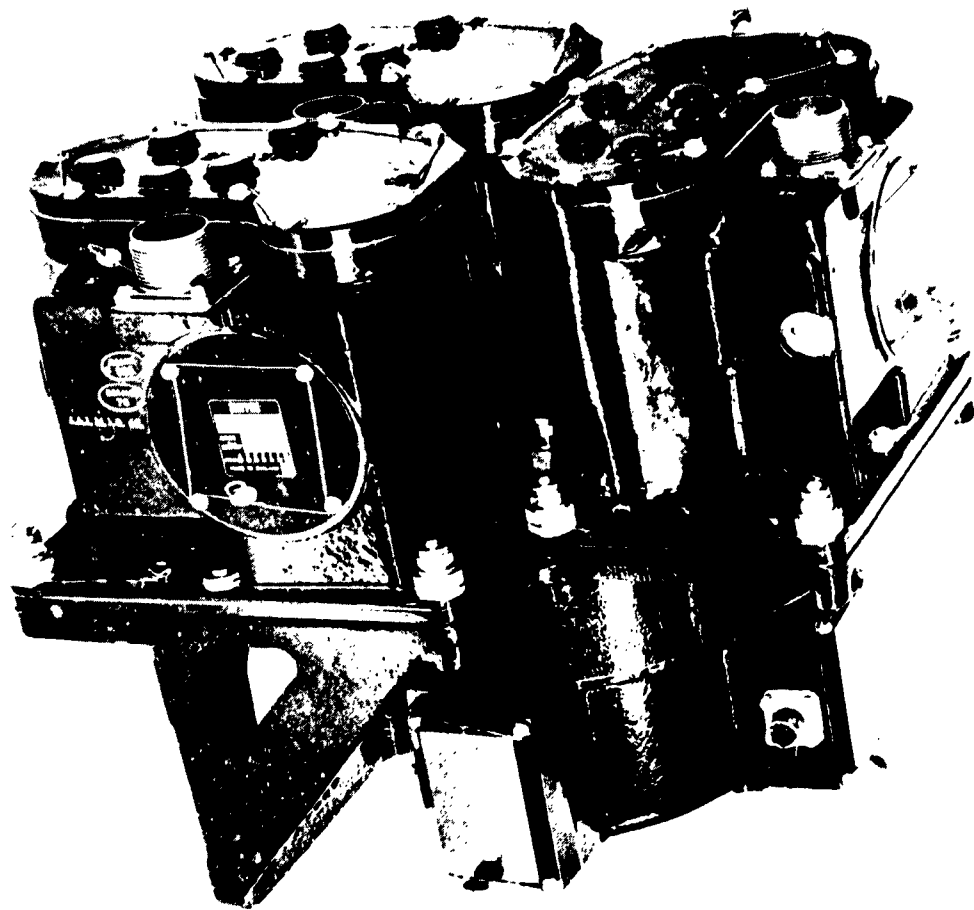


FIG. 3 TRIPLEX SERVOMOTOR ASSEMBLY

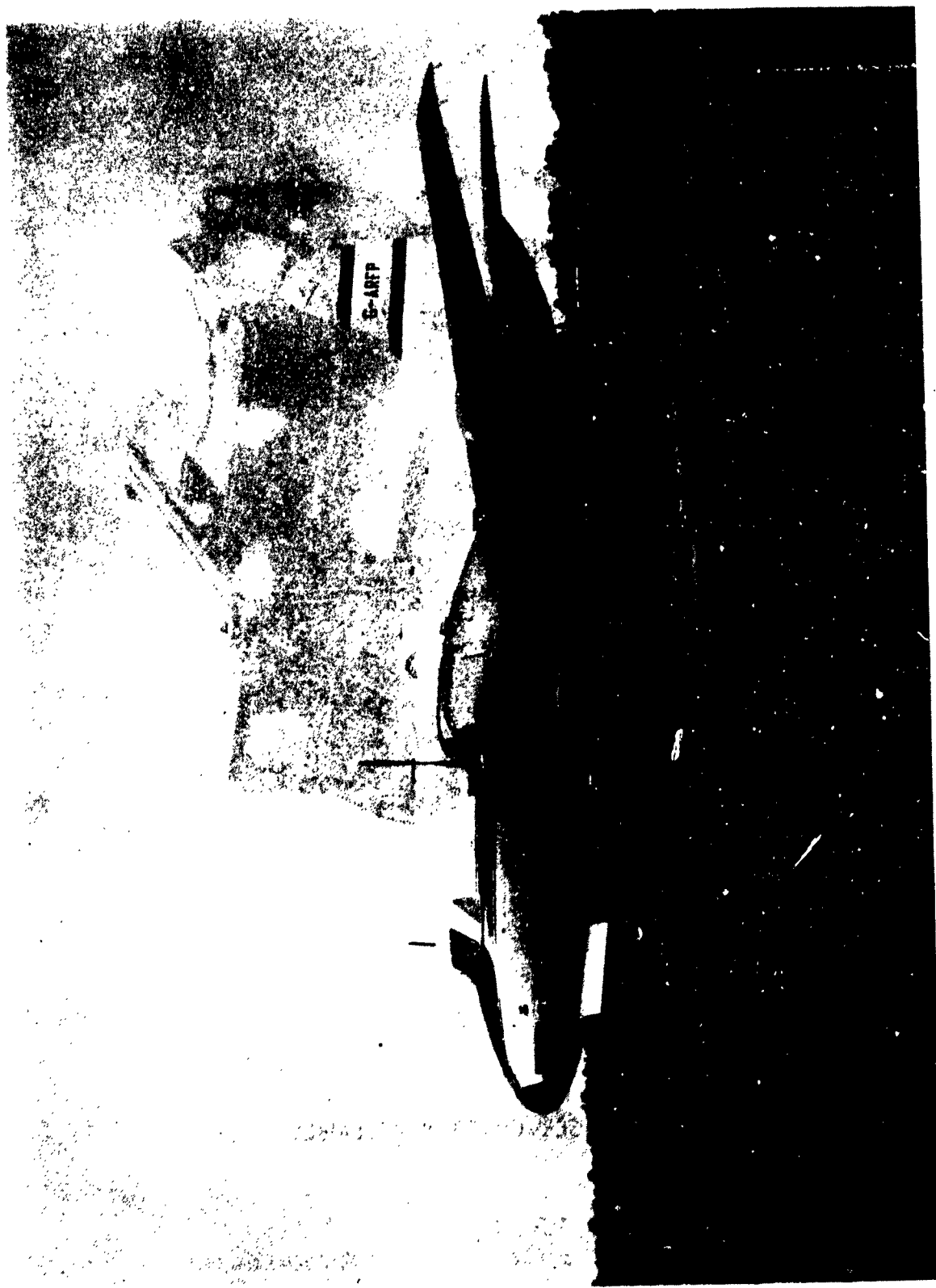


FIG.4 VARSITY TRIAL AIRCRAFT

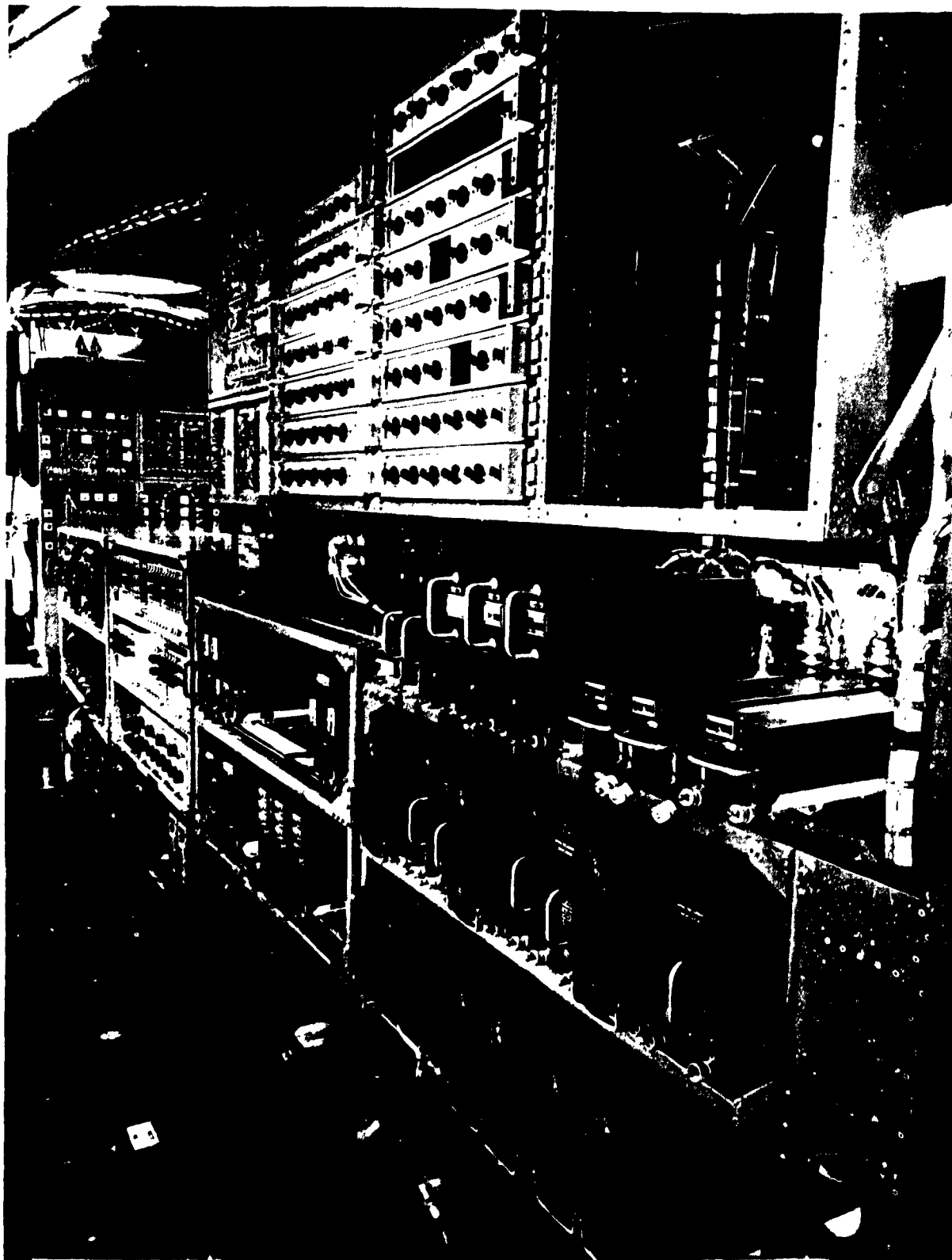


FIG.5 VARSITY TRIALS EQUIPMENT RACKS



FIG.6 VARSITY INSTRUMENT PANEL



FIG.7 VARSITY ROOF INSTRUMENT PANEL



FIG. 8 VARSITY DISTRIBUTION BOARD

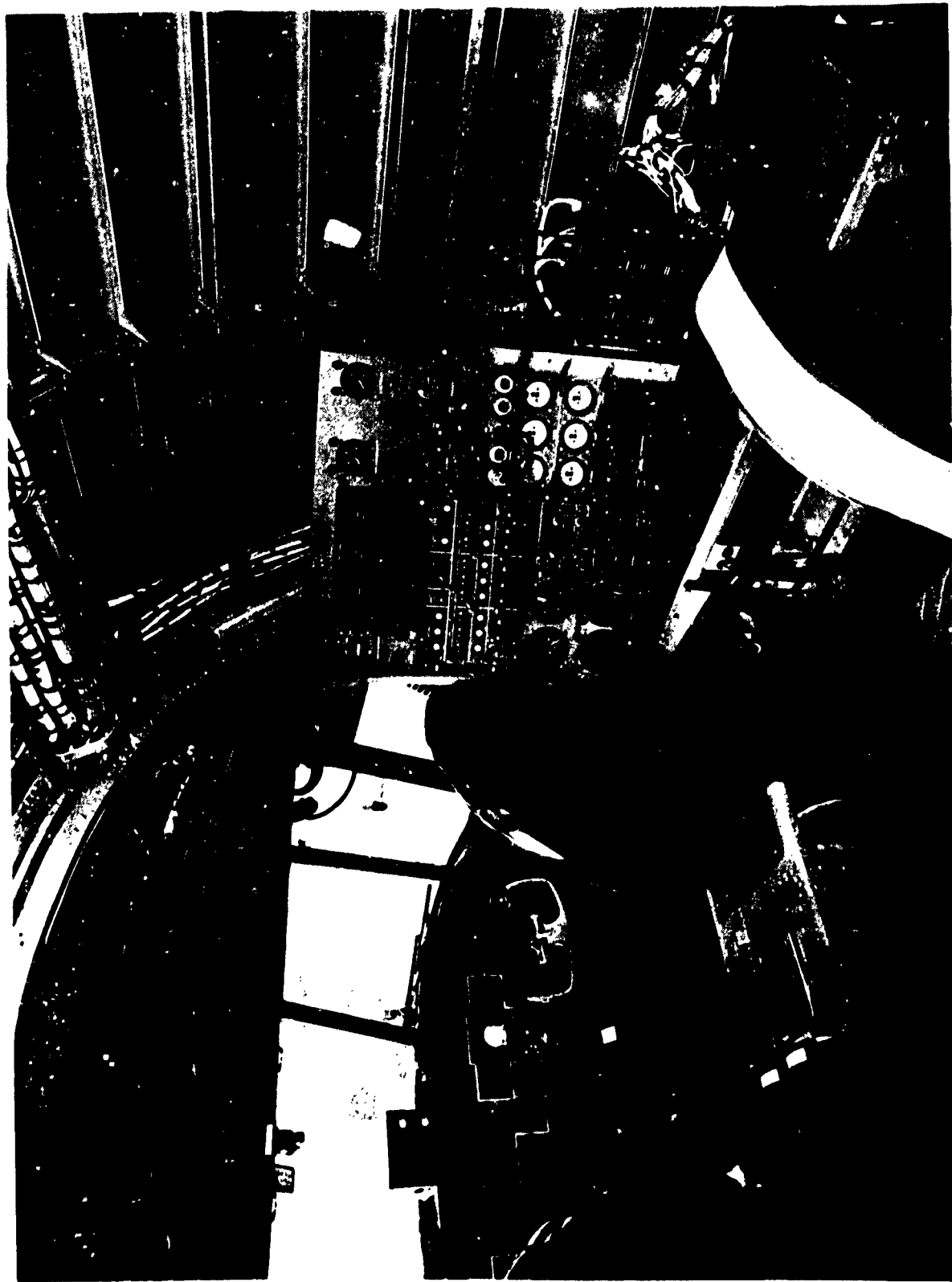


FIG. 9 VARSITY FLIGHT TEST ENGINEER'S STATION

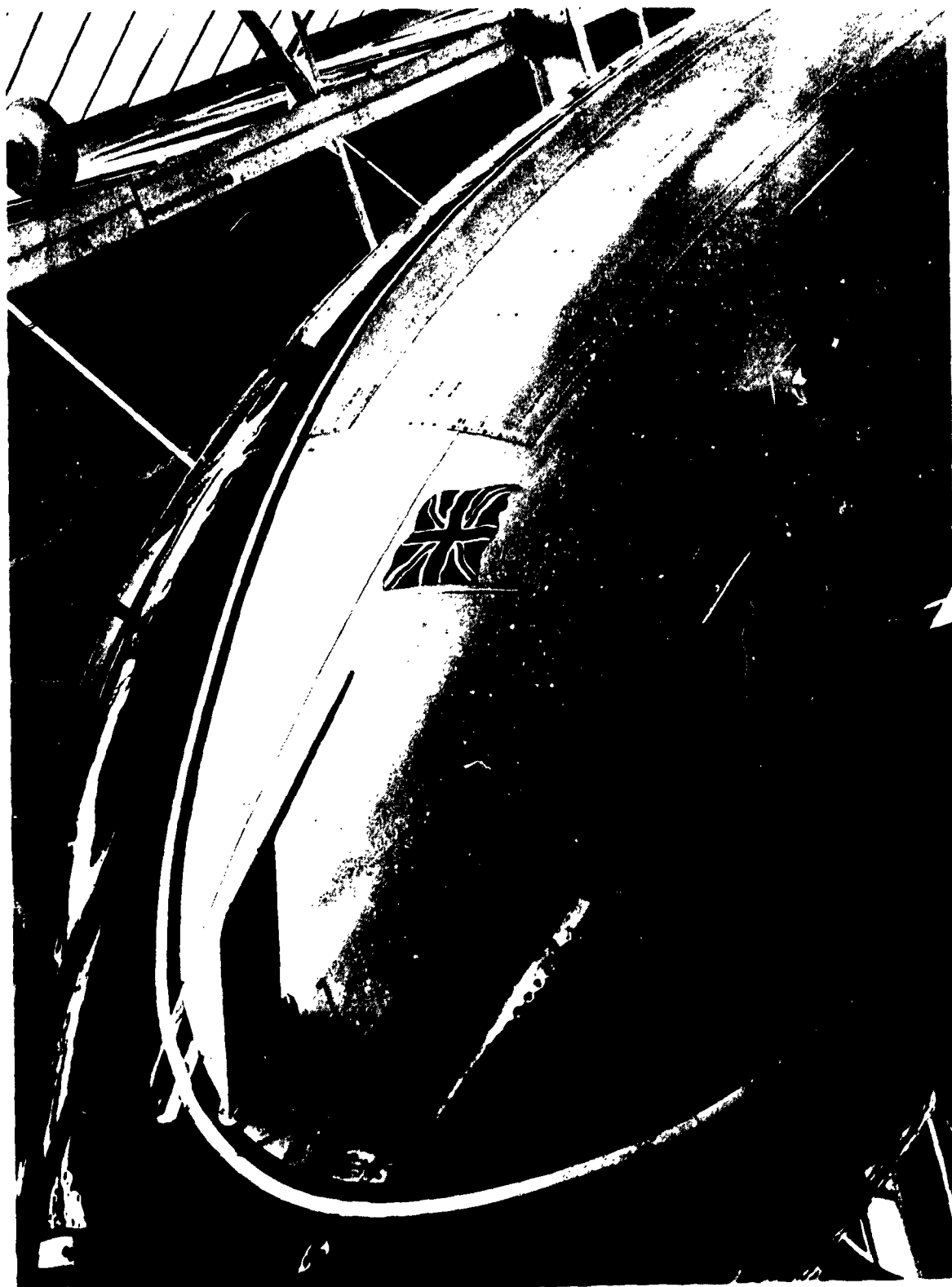


FIG. 10 COMET AREAL SYSTEM

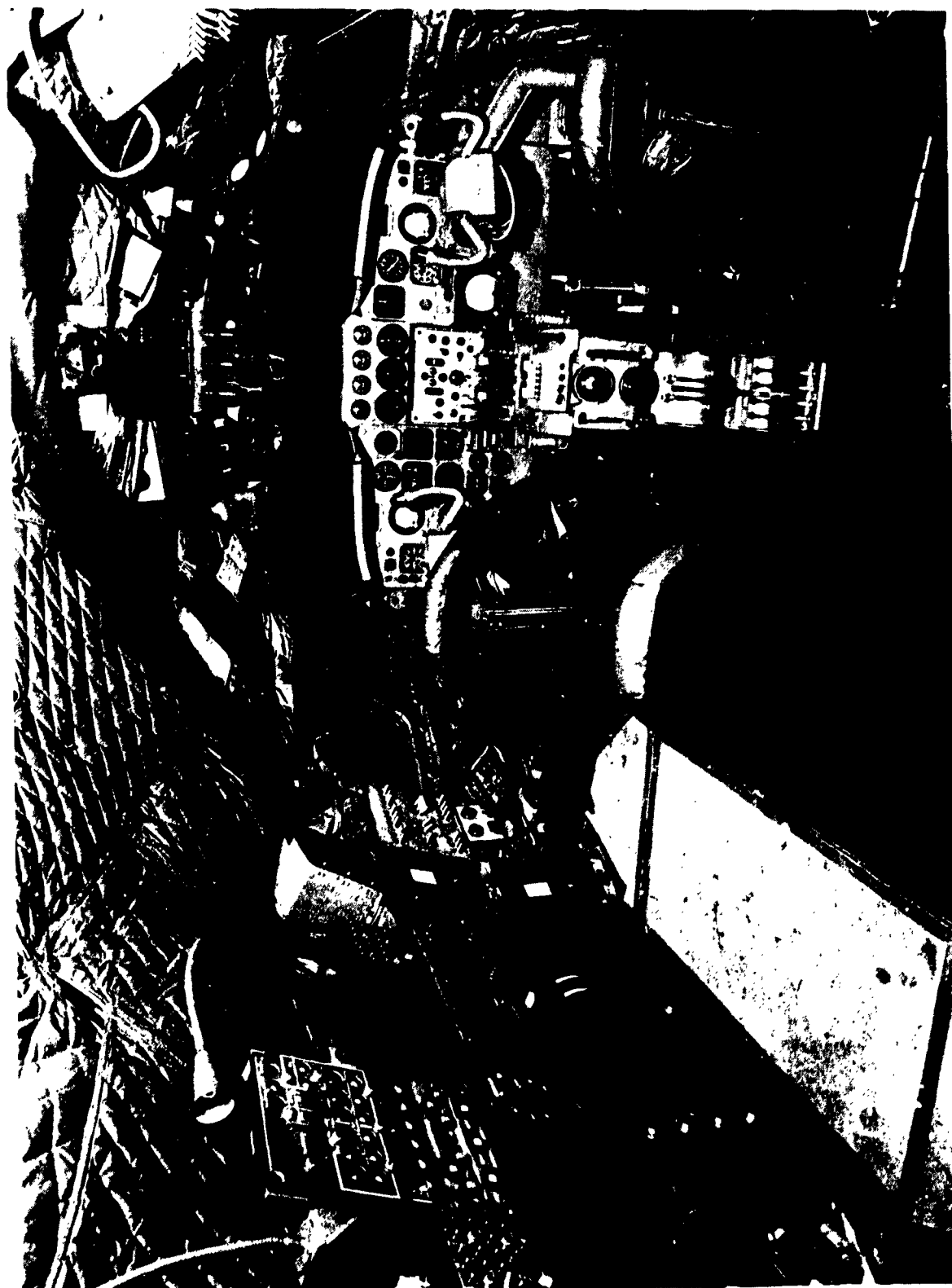


FIG. 11 COMET INSTRUMENT PANEL

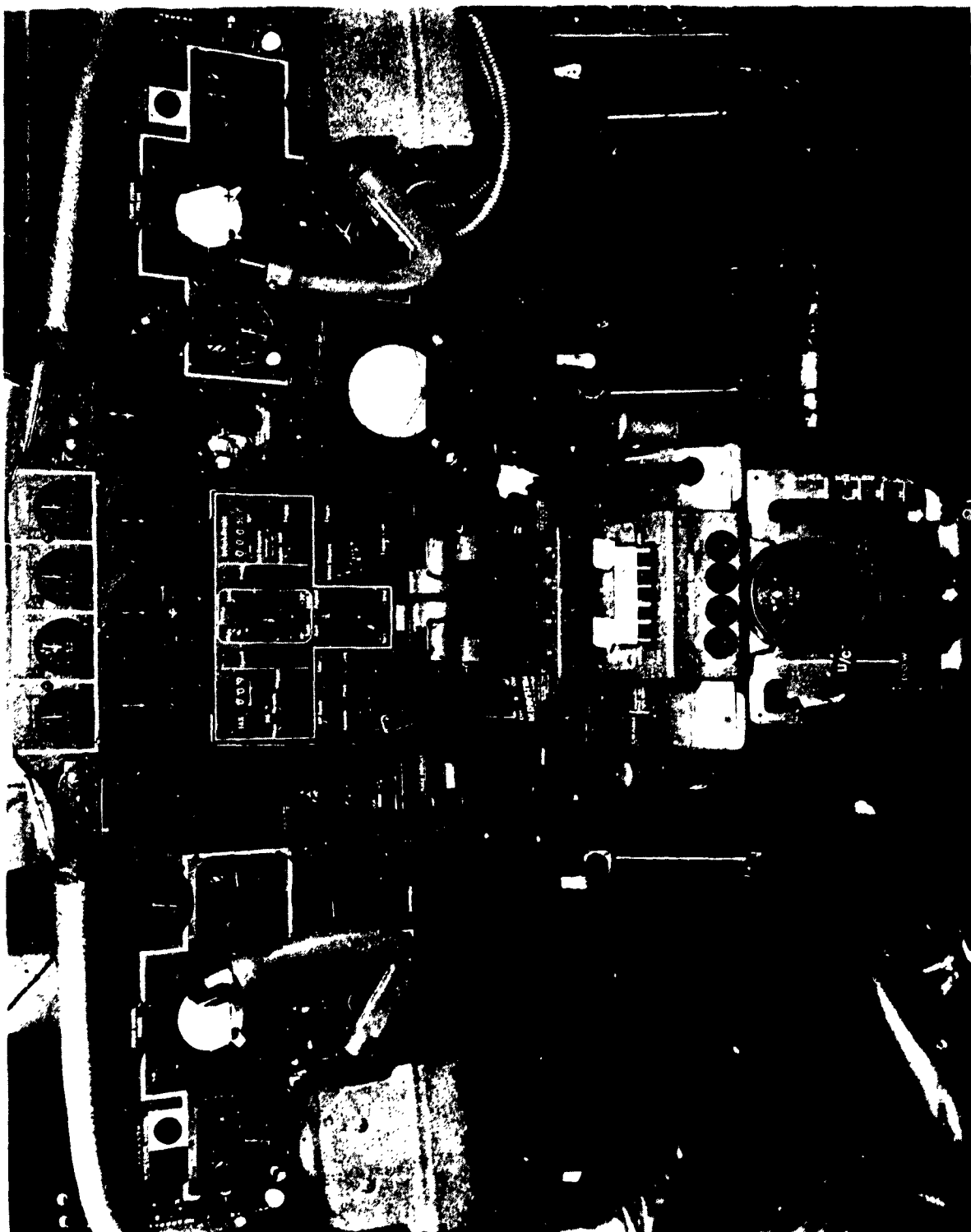


FIG. 12 COMET INSTRUMENT PANEL



FIG. 13 COMET MAIN CABIN

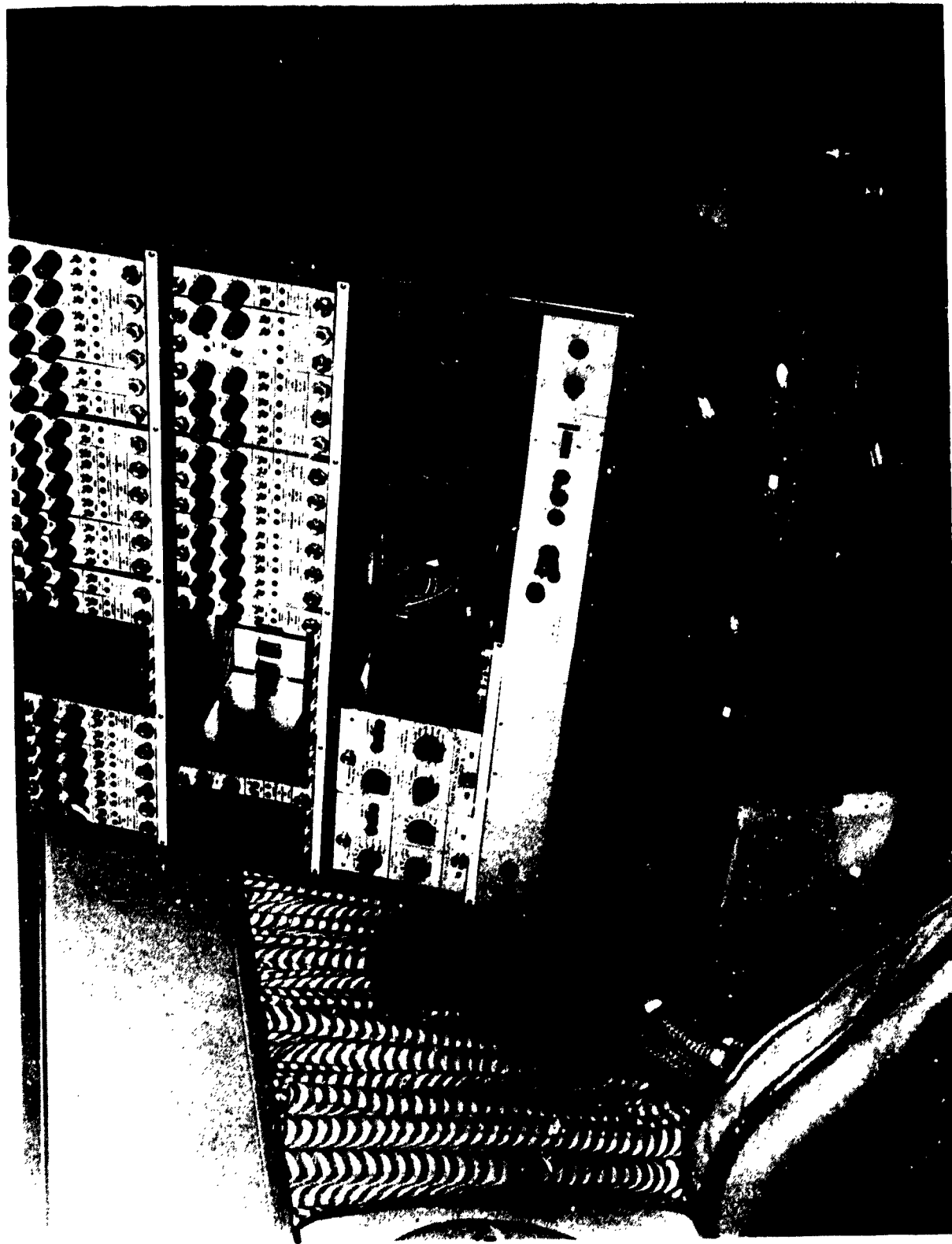


FIG. 14 COMET INSTRUMENTATION CONSOLE

**A REVIEW OF THE BOEING LOWER WEATHER MINIMUMS PROGRAM
FOR THE 707-720-727 AIRPLANES**

by

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Presented by

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at the

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A. Introduction

Soon after the airlines had gained operational experience with the current jet transports, they commenced their own individual programs to secure FAA approval for operation to the 200-1/2 weather minimums. Considerable effort and expense has since been expended by the airlines as well as the manufacturers and subcontractors to accomplish the necessary operational and reliability improvements in the automatic pilot and flight director systems. The familiarization and training portion of the program amounted to considerable expenditure on the part of the airlines also. Today, several of the 707/720 operators have obtained FAA approval to operate to the 200-1/2 minimums at certain airports. These same airlines have expressed their desire to operate to substantially lower minimums with the conviction that this can be done in a safe, practical and economically justifiable manner.

The Boeing Company has been actively studying and testing various items of equipment for operating to lower weather minimums since the 707 program got under way. The 707 prototype, otherwise known as the -80, was landed using automatic equipment in 1958 at Boeing Field. Two years ago, Boeing established a philosophy on which to hopefully build a program for airline operation to minimums well below the 200-1/2. The Boeing philosophy consists primarily of the recognition that a successful instrument landing system must be "pilot-oriented." Under both manual and automatic control the pilot must have positive assurance of proper functioning of his equipment as well as high quality flight path information. A symposium was held with the airlines in September 1961 at which tacit concurrence with the program for the 707/720 airplanes was obtained. The experience gained by the airlines and the results of studies by Boeing over the ensuing two years have helped to further define the operational philosophy and airborne equipment necessary to operate safely to the lowest practical and economically justifiable weather minimums.

Boeing now believes that the time has arrived for taking further positive action toward equipping the 707/720 and 727 for operation to minimums below 200-1/2. Consequently, incorporation of certain equipment into the production 707/720 and 727 airplanes is now definitely planned.

B. Boeing Lower Minimum Past and Current Research Effort - Conclusions

The Boeing research effort has been aimed at two objectives: first, to investigate the automatic and manual-instrument landing equipment

requirements for the 707 and 727 airplanes, and secondly, to evaluate the pilot monitoring requirements during the approach and landing.

Several automatic approach and landing systems have been studied. The Bell System and the North American Autonetics System, along with Boeing-developed glide slope extension and flare systems, were tested in the 707 prototype airplane. Glide slope extension schemes were evaluated on both automatic pilot and flight director. Successful landings were accomplished with the automatic pilot and also with the flight director.

Various devices and systems to aid the pilot in monitoring the approach were also tested. Para-visual displays, glare shield mounted indicators, radio altimeter height displays and combinations of information in the flight director were experimented with during hooded approaches and landings. Auto-pilot and flight director studies have been conducted using analog computers and partial simulators. Various methods of improving performance during the last stages of the approach are currently under investigation. Heads-up displays have also been investigated using partial simulators as well as aircraft.

These studies have helped define present equipment capabilities and shortcomings, and have illuminated the automatic landing problems peculiar to large jet airplanes. There is no doubt that, technologically, the automatic pilot and monitoring requirements can be met by many different systems under "laboratory controlled" conditions. The real problem here seems to be one of developing a system that has satisfactory and consistent performance and is reliable, and easy for the airlines to operate and maintain. Further, it is obvious that the necessary additional airborne equipment must be compatible with the immediate or near-future airport environment, as well as be able to be retrofitted easily to the existing fleets of jet transports.

Consequently, Boeing has concluded that it is now possible to economically equip the jet transport aircraft for IATA Phase II minimums (approximately 100-1/4). It is necessary, therefore, to assess the requirements for operating the aircraft safely to the lowest minimums where the pilot can manually conduct or safely monitor the automatic landing. These minimums are not defined at present and can only be determined by simulator evaluations, flight tests and service experience. Each airplane's approach speed and handling characteristics will greatly influence the actual safe minimums. Realistic analysis of approach path weather conditions including the effects of turbulence, windshears and convectivity must also be considered in establishing the performance objectives of the system.

In order to go one step further and obtain an idea of the equipment and techniques to be used in this program an estimate can be made as to the lowest practical minimums for the pilot to either safely monitor an automatic touchdown or disconnect and land manually. Based on the flight test in fog conditions at Arcata and Newark in earlier aircraft and more

recent tests at Andrews AFB and Otis AFB and our own collective experience, it is believed that with the airplane adequately aligned with the runway that a visibility of approximately 250 yards would be near the practical lower limit considering 10-15 knot crosswinds, gustiness, etc. It is also believed that under these conditions the pilot would need this visibility upon reaching approximately 70 feet of altitude to adequately monitor or conduct the flare and landing. High intensity approach and runway lighting are assumed to be installed.

It should be noted here that the Boeing philosophy considers an automatic touchdown capability to be a necessary part of the automatic equipment for operations to Phase II minimums. A successful go-around can then be accomplished from any height including after touchdown. It is hoped that the manually-conducted approach can satisfy the same ground rules. More studies on split axes operation and improved displays will help to settle this question.

It is perhaps appropriate to discuss here Boeing's view with regard to the "survivable electronics" philosophy. Essentially, this philosophy would reduce the statistical risk of electronic failure to one part in ten million for the critical 30 seconds preceding touchdown. It is essential, in considering this philosophy, to understand that the statistical probability of arriving at the station with all electrons aligned is something quite apart from the quoted number.

In any event, one cannot quarrel with the objectives of up-grading system reliability. The two questions which create the doubters camp are:

1. Are we sure we know how to achieve these reliabilities?
2. How much is it worth in weight, maintenance and initial investment?

Achievement of system reliabilities to very high orders are difficult even when all elements are under direct control. We at Boeing are becoming increasingly aware of the frequent occurrence of highly improbable events.

The 707 electrical system, which consists of four independent generating systems, has a minute failure probability, yet all electrical power has been lost on a revenue flight from what one might call a "common event." This "common event" can be caused by a single mechanic or a thimble-full of aluminum chips. Compounding the problem as regards automatic pilot-controlled landing is the fact the ground installations are not under direct control of the system designer. In short, the anticipation of all cumulative-type failures is a most difficult technical task in a multi-element interdependent system. Redundancy surely is a valid attack provided that potential

cumulative failures through inter-connections do not exist.

How much should one pay to raise survivable electronics probability above one part in one million? This certainly is a function of the individual airline.

We at Boeing believe that a period of operations to minimums below the present and above zero-zero is necessary for the maturing of all elements of the problem. However, we believe the installed (IATA) Phase II equipment should be capable of consistent touchdown under automatic control. We also believe that the energy management aspect of automatic landing systems (flight path and speed control) holds promise of reducing the landing accident rate for both IFR and VFR operations. We think we can achieve (IATA) Phase II operation without the penalties attendant to statistical failure-proofing. Further, considerations of dispatch reliability, DOC's and the unpredictable "common event" make us skeptical of having the ability at this point in time to achieve the desired level of safety necessary for routine zero-zero operations.

The international controversy on "All Weather" or "Lower Minima" solutions poses a first-order dilemma for an airframe manufacturer. The reasons are rather fundamental. The reception of the "solution" will vary with the airline's route structure, economic outlook, accumulated experience and the strongly held opinions to be found in most operations departments. This puts the manufacturer in the position of being damned if he does and damned if he doesn't on many of the equipment decisions available to him. Those who say "give any airline the equipment that it wants" are overlooking the fierce competitive pressures on basic airplane costs which can give the manufacturer the choice of over-pricing or under-equipping in approaching a potential customer. This exaggeration is used merely to illustrate the thorny nature of the "All Weather" subject which fact is amply supported by the very size and scope of this conference.

Let us now address ourselves to the actions which seem indicated at this point in time. The Boeing Company research program to date has been briefly described. Also available to us are the results of the extensive work performed in the United Kingdom, France and in the USA. A weighting of these results discloses some areas of general agreement and areas of controversy. From major controversy such as "survivability" to minor controversy such as surrounds automatic throttles there are a host of equipments and configurations which are heatedly debated. However, let us look at what we think a majority would agree upon:

1. The improved ILS will be used.
2. Some form of glide slope extension is necessary.
3. Automatic pilot failures below 100' must surely be passive.

4. Ground proximity indication is needed.
5. Automatic pilot performance must assure beam centerline bracketing under reasonable crosswind gradients and gustiness.
6. Windshield rain removal systems must be optimized.

Automatic speed control by throttle will be added to this list if the majority of the airlines agree that this is necessary or very desirable.

707/720 Lower Weather Minimum Program

The 707/720 airplanes being delivered in 1963 have been equipped with several automatic pilot and flight instrument improvements such as:

1. Navigation instrument warning system
2. Optimized flight director gain of Bendix System in approach
3. Improved automatic pilot disengage warning
4. Improved automatic pilot amplifier computer
5. Provisions for future addition of augmented glide slope and flare computer, as plug in modules, within the automatic pilot amplifier-computer.

The following items have been added to the program and will be incorporated in the airplanes on a timely basis.

1. Accentuated warning of localizer and glide slope failure by additional light and audible warning.
2. Improved automatic pilot with flare computer.
3. Full time yaw damper with integrated hydraulic actuator and yaw hardover protection.
4. Automatic approach monitor-roll and pitch axes.
5. Low-range radar altimeter.
6. Improved windshield rain removal system.
7. An optional automatic speed control system.

Design of the installations will be such that a minimum amount of airplane modification to retrofit existing models will be necessary.

Should aerodynamic differences necessitate variations in equipment we would endeavor to achieve such changes either by "plug-in" modules or by changes in the airplane installation. Every attempt will be made to maintain the identical basic equipment.

Some additional explanation to help in the understanding of the choice of program might be useful:

1. Improved Automatic Pilot Approach Capability

Accurate alignment on the glide and localizer paths and stability of the airplane during gusts, varying crosswinds, beam bends, etc. is extremely important during the latter phases of an approach. This will be achieved by sensing necessary parameters to damp and average the ILS information, yet providing primary guidance by ILS. Some additional performance capability will be required in the localizer control to give faster recovery to beam centerline under varying crosswind conditions. Certain promising techniques are being evaluated and the best practicable method will be implemented.

2. Flare Computer

An integral part of the engineering design of the current automatic pilot is the facility for addition of a flare computer within the automatic pilot amplifier computer. This design criteria was established during the September 1961 symposium. The automatic pilot portion of this feature will be implemented and may be considered to be an extension of the augmented glide slope but using information from a radar altimeter instead of the air data sensor used in the automatic pilot.

3. Full Time Yaw Damper

The current yaw damper is the rudder channel of the automatic pilot system which drives an electric servo. All automatic pilot inputs are felt at the rudder pedals. The new system as planned is generally as outlined during the September 1961 symposium utilizing a new series integrated hydraulic actuator which will cause no rudder pedal motion or forces. The rudder channel of the automatic pilot system will be used as the electronic package. The system will be similar to that being used on the 727 where the yaw input will be mechanically limited to five (5) degrees and no outside influences such as cable friction or pilot input can reduce the yaw damper effectiveness. Plus or minus five (5) degrees of yaw damping will always be available from any trim or pilot controlled position.

4. Automatic Pilot Approach Monitor

All 707/720 airplanes have facilities for installing an automatic pilot comparison unit. The new approach monitor will replace the comparison unit, will work under tighter tolerances, be more reliable, be limited in operation to approach modes only and would utilize existing space and

wiring provisions wherever possible. Assuming no relaxation of current regulations, such a unit would be required for operation to low minimums.

5. Low Range Radar Altimeter

This will be an additional system installation in the 707/720 airplanes.

6. Improved Windshield Rain Removal

For optimum visual ground contact some improvement is desirable in keeping the windshield clear under rain conditions. The recently developed Boeing rain removal system is simple and effective, consisting of a solenoid operated repellent fluid jet system for operation in conjunction with the existing windshield wipers. Two pressurized containers with manual selection are connected to a solenoid operated valve controlled from the cockpit. Operation of the cockpit control switch causes a jet of water repellent solution to be ejected onto both the Captain's and First Officer's windshield. Subsequent wiping by the wipers on the wet windshield produces a highly water repellent surface such that visibility in rain is vastly improved.

7. Automatic Pilot Throttle Control

Since this will be an additional new system which is not directly dependent on other systems and since the desirability for its use may be best determined by individual operators, the automatic throttle control system is planned to be installed as a customer option. Similarity to, and commonness with the installation on the 727 will be maintained wherever possible. The system will be fully engineered and evaluated concurrently with the other items.

As has been outlined the addition of the chosen systems occasions very little change to the electronic complement of the airplane. Further, the chosen systems are, insofar as practicable, derivatives of the current electronic installation. Accordingly, we anticipate that retrofit to all existing model 707/720 airplanes can be achieved without a considerable amount of rework or "time out of service."

727 Lower Weather Minimum Program

All airplanes of the Model 727 contracted for after January 1, 1963 will contain provisions for the following lower weather minimums equipment.

1. Dual Pitch Channel monitor and auto flare
2. Lateral control monitor
3. Instrument comparators (heading and attitude)
4. Radar Altimeter
5. Third attitude indicator
6. Automatic speed control system (optional)

Of these items, the customer may order the installation of equipment at his option. These features, coupled with provisions which have been installed in the basic airplane from its conception, will, in our judgement, allow operation to minimums of 100 feet and below. Boeing's reasons for offering these features can be explained as follows:

1. Dual Pitch Channel

The dual pitch channel is being installed to insure a passive type failure in the event of a hardover signal. A more simplified monitor could accomplish this; however, the dual pitch channel offers other significant advantages: (a) Accuracy of failure detection is improved (b) The dual elevator control system has been designed for primary control from either or both elevators, providing operational capability and safety (c) There is a logistics benefit arising from monitors and pitch channels being identical. (d) A Hydraulic failure can be sensed and compensated for in addition to the electronic hardover failure (e) The dual channel has the additional advantage that either automatic pilot channel may be operated independently for all functions other than lower minimums.

2. Lateral Control System Monitor

The lateral control monitor is being installed to prevent an inadvertent hardover aileron action. While this may not be a requirement for low approach certification, a simplified monitor will be installed as a conservative measure.

3. Instrument Comparison Warning System (Attitude and Heading)

Visual comparison of left hand and right hand instruments is currently the accepted method of detecting those failures which are not displayed by warning flags. Early detection of failure becomes more important when operating to lower weather minimums. A centralized instrument warning system, based on comparison techniques, is already flying on many Boeing airplanes.

4. Radar Altimeter

The radar altimeter is necessary since it is the only known

instrument that will give us the required accuracy in altitude reading above the terrain which is essential in this type of landing. This will be an important factor in giving the pilot the necessary confidence to allow the airplane to proceed to the minimum authorized height in conditions of poor visibility. It is being installed mainly as a flight instrument, but it will also provide other important functions during the approach.

5. Third Attitude Indicator

This instrument is being installed to provide back-up for the attitude comparator system. Instruments such as the airspeed and rate of turn could satisfy the same purpose; however, it is believed that a simple and direct reading attitude indicator can provide the desired information in a more useful form.

6. Automatic Speed Control

The optional automatic speed control installation will be simplified to the greatest possible extent. Although automatic speed control is being installed to increase the precision of the approach to lower minimums its use will not be restricted to this mode.

The following basic features of the 727 airplane supplement the above-mentioned items:

1. Lower landing speeds.
2. Excellent speed-thrust stability.
3. Improved aerodynamic speed brakes.
4. Improved reverse thrust and wheel brakes.
5. Improved windshield rain clearing.
6. Full time dual yaw damper.
7. Automatic pilot designed for tighter beam following under adverse weather conditions during the approach.
8. Automatic pilot with extended glide slope built-in.
9. Automatic pilot designed for operational flexibility with features such as split axes and all angle VOR and ILS capture capabilities.
10. Automatic pilot with built-in self-test for ease of maintenance.

C. Summary

Flights on the three 727 test airplanes have thus far indicated that the performance of its automatic pilot with the extended glide slope is equal to or better than expectations. The early recognition of the eventual 707/727 operation below current minimums has made it necessary to plan the basic 707 and 727 automatic pilots for maximum flexibility and growth capability. This planning includes provisioning for operations beyond Phase II so that transition to Phase III can take place in an orderly and economic manner.

**CATEGORY II OPERATION -
NO PERFORMANCE COMPROMISE**

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INTRODUCTION

U. S. commercial aviation has now arrived at a major milestone: the decision to begin an evolutionary approach to provide Category II Operation with the present high performance jet aircraft. Most of the airlines have already outlined a program they will follow in achieving this goal; many of the airlines have already taken the first step in this evolutionary approach to the Category II Operation. It is the intent of this paper to discuss some of the aspects that must be considered in determining the evolutionary steps to be taken. It is a further intent of this paper to discuss the results obtained in the Lear Siegler, Inc. (LSi)/SUD Aviation All-Weather Landing Program now being conducted in Toulouse, France, in the Caravelle, and to show how these results affected the final decisions in arriving at the operational configuration now being implemented in the SUD Caravelles. It is hoped that the dissemination of information about the practical experience obtained on this program, together with the reasons for certain decisions, can assist the airlines in formulating their own plans for step-by-step implementation of their equipment to attain the final goal of Category II Operation.

SUMMARY

In determining the aircraft implementation necessary for Category II Operation, there are three requirements which must be considered: economics, safety, and performance. However, before making a valid decision based on these requirements, it is necessary for the airline to define what it hopes to obtain from Category II Operation. There are three general approaches that can be taken to arrive at the final goal, and each of these approaches appears to require a different equipment implementation:

- ... Operation to 100-foot ceiling and one-quarter mile visibility
- ... Operation to some minimum RVR (e.g., 400 meters)
- ... Interim step to complete zero/zero operation

The first concept for Category II Operation is to select the suggested 100-foot ceiling and one-quarter mile visibility as the final goal, and implement the aircraft accordingly without further considerations at this time. There appears to be a general feeling that minor modifications of existing equipments can provide the required performance in meeting this

goal. However, if a more realistic look at the Category II minimum is taken, it will be realized that operation to 100 feet of altitude of necessity will be a look-and-see proposition; and, as such, an RVR (runway visual range) is a more realistic means of specifying minimums.

In actual practice, it is doubtful if the existence of a 100-foot ceiling can actually be measured or predicted accurately for the precise time and location over the ground where the pilot will be reaching a 100-foot altitude on his final approach. Usually these lower ceilings are ragged and/or obscured, and vary considerably over relatively small areas. In addition, the methods of measuring such ceilings do not provide extreme accuracy. This variation in ceiling consistency and measurement accuracy has been pointed out by the results obtained at Chicago's O'Hare Airport. Simultaneous readings have recently been made on two separate runways with independent measuring devices; very appreciable differences in reporting altitude were obtained.

Even without these factors, a pilot making an approach to 100 feet and one-quarter mile would normally undertake a "look-and-see" attitude. This means that if in reality a pilot is able to pick up the approach lights on an intermittent basis, and if he is right on course, he will in all probability elect to continue the approach to a lower altitude and will not abort as long as his visibility remains adequate for a visual landing (approximately 400 meters). Thus, practical considerations indicate that operation to 100 feet and one-quarter mile for Category II Operation is not a realistic concept, and the RVR method of specifying operational minimums for Category II Operation is more desirable.

Experience gained on the LSi/ SUD program has indicated that optimum performance is required to operate with an RVR of 400 meters, if safety and the frequency of missed approaches are taken into consideration. This performance cannot be provided by simple modifications of existing equipment.

The third concept in Category II Operation is to take the British approach and implement only that part of the full Category III system necessary to achieve Category II. However, it is doubtful if the economics can justify such an approach for U. S. carriers. Furthermore, it is considered impossible to finalize an adequate automatic landing system until considerable actual operational usage is obtained on such an automatic landing system under Category II minimums. An incident that occurred during the LSi/SUD program clearly demonstrates the need for a great deal of operational usage before committing a system to Category III zero/zero operation.

DETAILS

Let us look at the equipment that will probably be required and/or desired to operate to Category II minimums. In the first case, where a 100-foot ceiling and one-quarter mile visibility is used as the final goal, the following implementation would probably be required in the aircraft:

- ...Radio (radar) altimeter
- ...Path monitoring system
- ...Improved lateral path performance
- ...Improved longitudinal path performance
- ...Hard-over failure protection
- ...Optimization of the basic autopilot
- ...Go-around mode

Radio Altimeter: It is doubtful if any of the certification agencies in the U. S. or European governments will certify an aircraft in regularly scheduled passenger service to operate to a 100-foot ceiling without the benefit of a radio altimeter. From the pilot's standpoint, it is also highly desirable to have a radio altimeter on board, since it does give him that additional confidence that is required to assure him that he is in effect at the proper altitude.

Path Monitoring System: It appears quite mandatory that some form of a path monitoring system and pilot warning must be provided for operation down to 100 feet and one-quarter mile visibility. The limits to be monitored must be provided in the form of a "tunnel" in space, with the desired flight path in the center of this tunnel. The aircraft must enter this tunnel through a window at approximately the present minimums of 300 feet of altitude, and must stay in this tunnel until the new minimums of 100 feet are reached. If at any time the aircraft goes outside this tunnel, the path monitoring system must warn the pilot so that he can make a go-around without further delay. Since the pilot's ability to correct the path deviation prior to touchdown decreases with altitude, this tunnel must be conical or truncated, rather than cylindrical or rectangular. This means that the path monitoring system must monitor angular deviation from the path rather than pure displacement.

Improved Lateral Path Performance: It appears that none of the present-day automatic approach couplers or flight-director computers can provide the necessary performance for lateral direction to the 100-foot altitude without improvements.

Improved Longitudinal Path Performance: It is obvious that none of the present-day couplers or flight-director computers have the capability of providing the required performance to the 100-foot altitude point. This means that more precise flight path tracking must be provided. With any of the present coupling concepts, some form of glide path gain change to compensate for the convergence of the angular beam must be made, and some form of so-called glide path extension (memory) must be provided to arrive safely at the 100-foot level.

Hard-Over Failure Protection: For safety, the autopilot/airplane combination must be capable of being certified to operation to 100 feet of altitude under the present methods of certification for minimum altitudes with autopilot engaged. Some of the present autopilot/airplane combinations are already certified to altitudes of 100 feet or less, and have no further problem here. However, other airplane/autopilot combinations require some modifications or changes in order to allow certification for autopilot operation to 100 feet of altitude.

Optimization of the Basic Autopilot for the Approach Configuration: All of the autopilots in operation today are calibrated to perform at optimum at some compromise speed condition. In other words, an autopilot must be able to perform adequately at the high cruise condition and also in the approach condition. However, up to this time the emphasis has been more on the cruise condition, with a compromise in performance being accepted in the approach configuration. In order to operate to Category II, some optimization of the basic autopilot will have to be provided for the approach configuration.

Throttle Control: Automatic throttle control can be a controversial subject when it is considered as a requirement for Category II operation; but from a pilot's standpoint it is certainly desirable, because it relieved him of this function and allows him to devote more of his time and effort to monitoring the performance of the aircraft on the flight path. From this viewpoint alone it should probably be considered as part of the implementation requirements.

Go-Around Mode: As with throttle control, the requirement for a go-around mode for Category II Operation to 100 feet can be controversial, but it is felt that the desirability of a go-around mode (either manual or automatic) is well established.

Now consider the hardware implementation for the second concept to Category II Operation: that is, with the only limitation being an RVR of 400 meters. Some of the implementation requirements will remain the same as for the first concept of Category II Operation; other requirements will also be imposed. It is felt that the following items are requirements, or are highly desirable:

- ...Radio (radar) altimeter
- ...Path monitoring system
- ...Optimum lateral path performance
- ...Optimum longitudinal path performance
- ...Hard-over failure protection
- ...Complete optimization of the basic autopilot
- ...Throttle control
- ...Go-around mode
- ...Automatic flare
- ...De-crab
- ...Pilot display

Radio Altimeter: This is required for the same reason given for operation to 100 feet, and one-quarter mile.

Path Monitoring System: This must be provided for the reason given above, but in addition it must have the further capability of being able to monitor to altitudes lower than the 100 feet. It appears desirable for this monitoring system to remain operative until the flare is initiated.

Optimum Lateral Path Performance: In this concept of Category II Operation, the pilot will often be descending to altitudes which will bring him over the end of the runway and possibly to touchdown. Thus it is imperative that the best lateral path control be provided, even though it may be extending the present state-of-the-art.

Optimum Longitudinal Path Performance: As with the lateral path, control must be maintained to flare, and it is felt that the longitudinal path of the aircraft must be controlled with the highest accuracy obtainable even if it requires extending the present state-of-the-art. With the present glide path beams this appears to offer a major challenge, even though the accuracy requirements are not as severe as for the lateral path: particularly because with the present-day runways the longitudinal touchdown point does not have to be nearly as precise as the lateral touchdown point.

Hard-Over Failure Protection: In this concept of Category II Operation, the autopilot must have the capability of remaining engaged to altitudes well below 100 feet with safety. It is essential that the system contain adequate safety to protect against a hard-over failure at any altitude down to touchdown.

Complete Optimization of the Basic Autopilot for the Approach Configuration: It is thought mandatory that in order to obtain the optimum lateral and longitudinal path performance for the final phases of the approach, it is essential that the basic autopilot itself be optimized for the approach configuration including new concepts in automatic control.

Throttle Control: It is felt that automatic throttle control operation is much more of a requirement for operation to 400 meters RVR. This is especially true because most automatic flare systems require retardation of the throttles at the initiation of flare. This feature cannot be provided adequately as a manual input from the pilot.

Go-Around Mode: The go-around mode, either manual or automatic, is highly desirable and may be a certification requirement to operate to altitudes below 100 feet.

Automatic Flare: It is felt that automatic flare must be provided to operate safely to an RVR of 400 meters. With this concept for Category II Operation, the pilot will be descending to altitudes at which his flare should already have commenced. To assure the desired safety it is felt that the certification agencies in the U. S. and European governments will require an automatic flare mode for certification.

De-Crab: Some means of de-crabbing the aircraft must be provided, either automatically or as a manual maneuver by providing the pilot with the proper presentation.

Pilot Display: Operating with this concept, it is felt highly desirable that some panel instrument should supply the pilot with the same information that is being provided to the autopilot, so that he can adequately monitor the performance being obtained. This information can either be provided by a flight director computer modified to provide the same output as the autopilot computer, or by an independent output provided to the pilot display from the autopilot computer.

For the third concept of Category II Operation, which is an interim step to Category III Operation, all of the hardware that is necessary for operating to an RVR of 400 meters is needed. In addition, as an economic consideration, the system must utilize the same basic components and techniques which will be necessary to provide complete safety in the final Category III, or full zero/zero operation. This means that the system has to be designed with the final redundancy requirements in mind so that the system provided for Category II under this concept will furnish the basic nucleus for the final redundant system for the full zero/zero or Category III Operation.

In reviewing the first two concepts of Category II Operation in relation to the hardware implementation requirements, the following comments based on the experience obtained on the LSi/SUD development program are offered:

Radio Altimeter: This is a firm requirement in both concepts. In the first concept (100 feet and one-quarter mile) a radio altimeter of less accuracy could be utilized. However, unless an airline already had a radio altimeter of this type, there would be no appreciable initial economic advantage in going to a radio altimeter of lesser accuracy.

Path Monitoring System: This is also a firm requirement in both concepts. If the aircraft is not within a specified "window" at some minimum altitude, then the approach to 100 feet or 400 meters RVR should not be continued. The only difference is that in the first case the monitoring system operates to 100 feet, while in the second it must operate to the flare altitude. However, this should not require a change in implementation.

Improved Lateral and Longitudinal Path Performance: In considering the first concept of Category II Operation, i.e., operating to 100 feet and one-quarter mile visibility, the natural tendency is to modify the existing equipments with minimal changes. With the improved directional localizer beams and with various schemes of glide path extension, it appears feasible to modify the existing equipment for operation down to 100 feet and one-quarter of a mile. However, with the experience obtained during the LSi/SUD program, it appears that the wind shear, or wind gradient, can be much more severe than thought at present and thus there will probably be many more missed approaches than are now experienced with the present equipment operating to the present minimums. This can have an adverse effect on the whole Category II Operation in that if missed approaches

become quite common, the pilots will not have the confidence in the equipment necessary to encourage them even to attempt approaches under the 100 feet and one-quarter mile conditions. The generally-discussed wind gradient for the final approach configuration is four knots of change per 100 feet of altitude, and it appears that any of the present equipment with minor modifications is capable of coping with wind gradients of this magnitude.

The experience obtained during the LSi/SUD program indicates that this gradient in practice is much more severe than generally accepted, and it also appears that this gradient becomes more severe as the altitude decreases, due to the effects of the ground on the air mass. Fore and aft wind shears of 30 knots per 100 feet of altitude, lasting for periods of eight seconds, have actually been recorded by rather complete instrumentation on at least three of the automatic landings made in Toulouse. The terrain at Toulouse is relatively level, and would not be considered conducive to causing such wind shears. The weather conditions at the time these occurrences were recorded did not appear to be abnormal.

The wind shear, which was recorded as occurring during the flare, caused the aircraft to strike the runway with no apparent change in flight path angle and caused an extremely hard landing (somewhat cushioned by the ground effect). If this same fore and aft wind shear had been obtained during a manual landing, it is doubtful if the pilot would have been capable of counteracting the effect sufficiently to make a smooth landing. It is felt that some of the normal manual landings, which resulted in excessively hard runway contact and in which the pilot had difficulty analyzing afterwards where he erred, may have been the result of just such wind shears.

Figure 1 is a flight recording (taken in a Caravelle) of a normal automatic landing. Figure 2 is a flight recording of the same type of automatic landing in the Caravelle in the presence of the severe wind shear described before. It should be noted, in referring to the two figures, that in the case of the normal landing, the air speed decreases about three knots from initiation of flare until touchdown. However, in the case of the severe wind shear, it is apparent that the air speed decreased far in excess of the three knots; if extrapolated off the paper, a decrease approaching 20 knots could be shown. Also, in reference to the two figures, note that the aircraft elevator position normally increases about three degrees during the flare, but in the case of the wind shear the

elevator position increased over six degrees. Even with this, the wind shear effects were so severe that the automatic landing system was capable only of maintaining the rate of descent existing at the time of initiation of flare. It is realized that this severe wind gradient occurred during the flare; when considering ceilings of 100 feet, this would be in the manual realm. However, longitudinal wind gradients do occur far in excess of the four knots per 100 feet, even during the so-called glide path extension phase. Figure 3 indicates the flight path deviation occurring with and without positive glide path control from 250 feet to initiation of flare in the presence of wind gradients. Because of this, it was felt highly desirable to maintain positive glide path control until initiation of flare. The glide path beam signal characteristics are not as good as with the localizer beam, and the beam convergence is much more severe. Thus it is impossible to maintain positive glide path control with adequate gain margin to the initiation of flare by any modification of the existing coupler systems.

On the LSi/SUD program, it was found that an entirely new concept of glide path control had to be evolved in order to maintain positive path control until the initiation of flare. No system which uses a memory type of glide path extension scheme can provide the accuracy desired for a low-minimum program in the presence of severe wind gradients which appear to be more prevalent than might be expected.

Experience on the LSi/SUD program has also indicated that wind gradients approaching the same magnitude appear in the lateral case. Crab angles of 15 degrees have been experienced at 150 to 200 feet of altitude with the touchdown occurring with a zero crab angle. At the approach speeds of the Caravelle, this is equivalent to a cross-wind gradient of 16 knots per 100 feet, which is far in excess of four knots per 100 feet. None of the present-day lateral couplers can cope with such a gradient, even when optimized for a directional localizer beam. Early analytical tests in the LSi/SUD program pointed out the fact that in the presence of wind shear a new technique in lateral coupler control had to be developed, or excessive missed approaches would result for any type of lower minimum program. The lateral coupler developed in the LSi/SUD program in addition to being optimized for the directional localizer beam, eliminates the heading signal and features new design concepts. This provides a coupler that will cope with most of the probable wind gradients. In tests with the L-102 autopilot coupler now standard in the Caravelle, a 12-knot step input of wind change laterally resulted in a 165-foot

lateral deviation before corrective action caused a return to the beam center. This maximum lateral deviation occurred 18 to 20 seconds after application of the step input. The same 12-knot step input in the new lateral coupler in the LSi/SUD program produced only a 13-foot deviation, which occurred within eight seconds after initiation of the input, at which time corrective action was initiated to return to beam center without overshoot. If this wind shear had been obtained at 200 feet of altitude, the existing L-102 coupler would have landed the airplane off the runway. Any heading-stabilized coupler will have the same difficulty in correcting for these lateral wind gradients.

The wind gradients actually experienced in the LSi/SUD program disagree with the information presented in RTCA SC-79, which is the source of the presently accepted four knots per 100 feet. However, the larger figures obtained on the LSi/SUD program are not the result of an isolated occurrence; also, they are well documented, and as such should be considered valid. For this reason, it is felt that a mere modification of existing couplers is completely inadequate to meet the requirements of lower minimums for either the concept of 100 feet and one quarter of a mile or for the concept of an RVR of 400 meters. We cannot afford to have more missed approaches at these lower minimums; if we do, the whole lower minimums program will be defeated. In view of the fact that it is rather difficult, or impossible, to simulate a severe wind gradient in actual flight tests, the certification agencies should require a demonstration (on an analog computer) of the capability of both the lateral and longitudinal computers in correcting for severe wind gradients. On an analog computer it is relatively easy to simulate any desired wind gradient.

Hard-Over Failure Protection: In the case of the 100-foot ceiling, hard-over failure protection would have to be demonstrated only down to a 100-foot altitude. However, as indicated previously, if the ceiling were actually somewhat lower than 100 feet at the time the pilot reached his 100-foot altitude, due to the approximate one-second time lag of the pilot and the fact that another one and one-half seconds are consumed after the pilot initiates go-around before the aircraft starts changing its flight path, it would be quite easy to have the autopilot engaged inadvertently down to an altitude of 75 feet or lower. For this reason it is felt that hard-over protection must be obtained in some other manner than the present torque-limiting procedures which cannot possibly result in a certified altitude much below 100 feet. On the LSi/SUD program, the initial certification will be attempted for 100 feet

and one-quarter mile. This is because the L-102 autopilot/Caravelle combination can be certified down to an altitude of 90 to 100 feet in its present configuration.

As indicated, it is felt that this is an inadequate means of protection from a practical operational standpoint. For this reason an active development program is under way which is a continuation of the LSi/SUD program to develop an autopilot fail-soft monitor (Safe Limit Protection Circuits). It is felt that the path monitoring system is adequate in providing the necessary monitoring for a soft (or passive) type of failure. Thus, if an autopilot can be made to fail soft under all conditions, within very restrictive changes in aircraft attitude, it will be possible to operate the autopilot safely to touchdown as long as the pilot can visually monitor the flare and landing phase of the approach. The LSi/SUD fail-soft concept has already been developed and the first flying breadboard has been fabricated and flight tested with highly encouraging results.

Redundant or monitoring systems are probably adequate in providing this same fail-soft (passive) feature; however, it was felt that the technique developed in the LSi/SUD program was less complex and was simpler to implement. Space provisions have already been allocated for this fail-soft feature in the production LSi/SUD All-Weather Landing System. It is hoped that flight test results of this fail-soft feature can be introduced into the production hardware before the first operational use of this system by an airline, which will probably be in the autumn of 1964.

Optimization of the Basic Pilot: In order to obtain the optimum lateral and longitudinal path performance necessary to cope with wind gradients, it was discovered early in the LSi/SUD All-Weather Landing Program that it was essential to optimize the autopilot for the approach configuration. The first approach was to optimize only the gains of the existing autopilot. However, it was determined that a rather large improvement in both lateral and longitudinal path performance could be obtained by providing signal shaping optimization of the attitude, rate, and servo feedback signals. In trying to implement this in the standard L-102 autopilot, it was found that a very complex switching method was required at the time the automatic landing system was engaged. From a complexity and a reliability standpoint this was certainly very undesirable. The decision was thus made to provide the optimum autopilot within the lateral and longitudinal computers of the All-Weather Landing

System. This minimized switching considerably and did not increase the complexity of the overall system. Thus with the present system, when the all-weather landing computers are engaged, all of the major autopilot signals are switched out of the existing autopilot and into the All-Weather Landing System. The only parts of the autopilot that are used during the final approach are the servos and the servo amplifiers. Another consideration in this decision was the extent of change that would be required in the existing autopilot. With this concept of providing the optimized autopilot within the automatic landing computer boxes, the changes to the existing autopilot are quite negligible and can be accomplished by a technician on a retrofit basis within an hour or two.

Throttle Control: In a system which will be used only down to 100 feet of altitude, automatic throttle is certainly not a requirement (although highly desirable). However, in a system that will be used to some altitudes less than 100 feet, which could include the altitude required for the flare initiation, the automatic throttle control becomes much more of a requirement. It is impossible to execute a satisfactory flare without retardation of the throttles. This would not be a desirable manual maneuver to have accomplished at 50 feet of altitude, since it would require some pilot monitoring which is better spent in monitoring other aspects of the approach. As a result, it is felt that automatic throttle control will probably be made a requirement by the certification authorities for operations at altitudes below 100 feet. But as indicated before, from a practical operational consideration the 100-foot minimum would actually be exceeded more often than not when the altitudes are in effect at the 100-foot levels. Thus it is felt that automatic throttle control should be part of any lower minimum system.

Go-Around Mode: During the early part of the LSi/SUD program, the go-around mode was considered, but it was decided at that time that it was a luxury feature, and as such would not be essential to the developed system. However, it was agreed that before completion of the flight test program the go-around mode would be implemented and evaluated in actual flight tests. This flight evaluation has now been completed and the results of the flight tests of the automatic go-around mode were so satisfactory and proved to be so desirable from the pilot's standpoint that the decision was made to implement the automatic go-around mode in the production system. Thus the

production system will include the automatic go-around feature with a separate output for presentation in a pilot display in case the manual go-around mode should be desired.

The concept employed to implement automatic go-around in the LSi/SUD program was that of utilizing existing signals so that there would be no requirement for switch-over to a signal that was not already being presented to the pilot. In the LSi/SUD All-Weather Landing System, the primary longitudinal control is instantaneous vertical velocity; hence the decision was made to introduce a vertical velocity command signal into the existing system. For additional reliability, this command signal is introduced via isolated inputs through the individual microswitches of each throttle. A rate of climb that can be maintained is commanded in the case of the Caravelle, for a single engine with full power. Present thinking is that this go-around mode will be used only for the first few seconds after the decision has been made to abort the approach. As soon as the climb has been firmly established, the pilot can then switch over to some other mode of operation.

Actual in-flight recordings of the automatic flare and go-around functions have shown that the aircraft flight path continues at the same rate of descent for about one and one-half seconds after the flare or go-around mode has been initiated. At a rate of sink of 10 feet per second, this means that the aircraft has proceeded 15 feet below the altitude at which initiation was effected. If it is now considered that the human pilot has a one - to two - second time lag in making the decision to initiate the go-around, it is evident that it is possible for the airplane to descent 30 or 40 feet below the minimum altitude before establishing a positive vertical velocity. For this reason it is felt that the go-around mode should be a requirement even for operation to 100-foot minimums.

Automatic Flare: From the standpoint of safety considerations, both the certification authorities and the operational users will require an automatic flare system for operation to altitudes below 100 feet. With present jet aircraft, the flare must be initiated before reaching 50 feet of altitude to prevent the necessity for an abrupt maneuver during the final phases of the flare and landing. From a safety standpoint, the automatic flare feature is quite essential for operation to an RVR of 400 meters, where the corresponding altitude may be as low as 50 feet. Under these conditions the pilot will be making every effort to establish visual contact and might not realize that he was passing through the minimum flare altitude.

The automatic flare feature is probably quite desirable for operation to the 100-foot altitude because, as discussed previously, in practical operations the pilot will in effect exceed this 100-foot minimum limitation quite frequently due to ground measurement inaccuracies and variable ceiling characteristics. There is probably a very good chance that the certifications agencies will not certify a lower minimum system to operate to either 100 feet or 400 meters RVR without an automatic flare feature.

De-Crab: The de-crab feature is certainly not a consideration for operating to 100 feet of altitude. Also, it is not a consideration for operating to any altitude where it is thought that a manual landing would be effected. However, in any system where an automatic landing will be made, the de-crab feature certainly warrants consideration. The question of whether the de-crab should be performed automatically or whether the information should be presented to the pilot cannot be answered readily. Implementation of the automatic de-crab is relatively straight-forward and does not provide a major technical challenge. But from the reliability and safety aspects, the automatic de-crab feature is somewhat questionable. The de-crab function must occur at a very low altitude: in the case of the Caravelle this is about 12 feet. The de-crab signal must necessarily be an entirely new signal that is switched into the system at that particular time. In the event of a passive malfunction of the de-crab signal, it is questionable whether the pilot would recognize the fact that the de-crab had not taken place in time to provide a completely adequate manual de-crab. The application of a de-crab signal of the opposite phase could in turn be even more catastrophic. In addition, compass system tolerances and the requirement for the pilot to set-in the proper runway heading pose additional problems.

At the present time a final decision has not been made on the automatic de-crab for the LSi/SUD All-Weather Landing System. The decision has been made to provide the production system with both an automatic function and a pilot indication, so that either automatic or manual de-crab may be implemented. If some users should decide that they would like to have the automatic de-crab function, it could be adapted to their systems; if they do not wish to have it, they have only to supply a jumper across two terminal points to exclude this feature during the flare phase. In any case, an indication will be provided for manual de-crab.

Pilot Display: For any lower minimum system, in addition to the path warning monitor, it is felt that the pilot should have available to him on some instrument the same output that is being introduced into the autopilot for automatic control. This provides the pilot with a little more confidence in his role of monitor during the final phases of the approach. For this reason the Caravelles which will have the All-Weather Landing System will be provided with the necessary switching to allow the pilot to monitor the output of the automatic landing coupler on flight director needles. In addition, the pilot will be given the capability of using the output of the landing computers on the flight director needles to accomplish a manual approach. Actual flight tests and numerous simulator tests have shown that the pilot can make a much better manual approach using the output of the new-concept longitudinal and lateral computers than he can with any of the standard coupler concepts presently in use.

In summary, it appears on the basis of practical considerations that Category II Operation will be an RVR type of operation; whether a ceiling limit of 100 feet is established or not, the pilot will in all probability be operating as he would with the establishment of a 400-meter RVR. Thus it appears that the implementation of a system for Category II Operation should include most of the features for automatic touchdown. In view of the severity of wind gradients encountered under actual conditions, it is absolutely necessary that the autopilot and the couplers be designed for optimum performance by taking a step forward from the present state-of-the-art. If this is not done, the frequency of missed approaches may cause the defeat of the whole lower weather minimum program.

Thus one might say that in view of the foregoing, it might be better to operate to Category II with the British concept, which considers Category II as merely the stepping stone to Category III, zero/zero operation. Two factors weigh against this concept: the first is the economics - it is doubtful if any of the U. S. operators can justify the implementation of the British triplex system on this basis. The second factor against such a concept is the fact that there are too many unknowns in the operational use of an automatic landing system. It should be pointed out here that more than 400 landings were accomplished during the LSi/SUD program before this severe wind gradient, which caused the aircraft to contact the runway at the same rate of descent that was established at the initiation of flare, was encountered. Because of the inability of the automatic flare system as developed to cope with this magnitude of wind gradient, the longitudinal computer for the SUD Caravelle was modified to provide a satisfactory flare even under these conditions. It was possible on the analog computer to directly duplicate the results obtained

in the actual landing by applying a wind gradient of 30 knots per 100 feet during the last eight seconds of flare. Figure 4 is an analog computer run of a normal automatic landing. Figure 5 illustrates the same condition with the simulated wind gradient. Starting from this point, it was possible by modifying the longitudinal computer and throttle control systems to cope with such a wind gradient and effect a satisfactory flare on the analog computer. Figure 6 is an illustration of the operation of the system, as modified, in the presence of wind shear. This implementation has now been incorporated in the actual production hardware in the Caravelle, but it may be some time before the actual conditions are again encountered to determine if the analog computer solution is valid under actual conditions.

This one incident did not occur until after 400 landings had been made during the flight test program. What other incidents of completely different character may occur when the automatic landing system gets into operational usage in many aircraft? Is it desirable, then, to commit oneself to a zero/zero landing system before such a system has been tried for several years under actual operational conditions? Only after extensive operation could one feel reasonably sure that all of the considerations affecting safety had been taken care of in the final system design. This means then that the concept for Category II Operation should be to provide the best possible system with fully automatic landing capabilities. The operational usage of this system in Category II Operation, while the pilot is still able to visually monitor the flare and landing, will provide a safe method of determining the suitability of an automatic landing system. After a system has been evolved in this manner, the decision can be made whether or not it is economically sound to go to the redundancy required for zero/zero operation. It may be that some new electronic technical breakthrough by that time will be able to provide the pilot with suitable visual information during zero/zero operation and thus eliminate the requirement for going to a multiplex system for safety reasons.

We feel that the system evolved on the LSi/SUD program has made the necessary step forward in the state-of-the-art to allow safe and repeatable operation in the presence of all the known factors at this time. We further feel that certification of this system for use to touchdown under Category II conditions will result in major benefit to the industry in determining the requirements for a Category III system, and at the same time will provide maximum safety for operation in Category II weather. Do we dare take a compromise in performance and/or safety for Category II Operation?

CONCLUSION

The LSi/SUD All-Weather Landing Program represents a progressive evolution based on experience, and recognizes the desire of the human pilot to remain master of the craft at any time during flight. Therefore it has been felt mandatory that the pilot must be provided with as efficient a system as possible: an automatic flight control system capable of executing automatic landings reliably and safely, and an information system permitting the pilot to monitor the operation of the automatic system and to take over at any time either to execute a go-around or manual landing. The system will permit attainment of lower operating minimums soon after its introduction. From the beginning of design, space and wiring provisions were made for later implementation of safe-limit protection circuits to provide a fail-passive characteristic of the autopilot with minor perturbation of the flight path, and to simultaneously alert the pilot. Autopilot operation under visual monitoring will thus be possible down to the touchdown and during ground run.

It is felt that the present autopilots and couplers in jet aircraft can be improved for Category I operations, but do not have the performance capability to provide reliable, safe operation under Category II conditions without major modifications. If it is desired to keep aircraft modifications to a minimum for economic and operational reasons, it is simpler and more economical to design the optimum autopilot parameters for final approach into the all-weather landing computers, thus simplifying the retrofit program as far as the autopilot is concerned. Positive glide path control to flare is deemed essential; the normal glide path extension schemes are not found to be adequate in providing the necessary longitudinal touchdown accuracy in the presence of fore and aft wind shears. These wind shears in practice were found to be much more severe than generally acknowledged. Radio altimeters are believed essential for operational safety both for Category II and Category III operations; automatic flare may be a requirement by the certification agencies for Category II operation since operational procedure for Category II will be a look-and-see operation and the 100-foot ceiling restriction will in reality be ignored for the more practical 400-meter RVR limitation. The automatic throttle control system, while not critical, is a highly desirable function from the pilot's viewpoint and is probably a requirement with automatic flare; the automatic go-around mode is likewise desirable. The de-crab problem must be resolved for Category III operations; the automatic de-crab system which has been developed performs well, but due to the need to set in a correct runway heading and related tolerances of the compass systems, as well as other operational problems, there is not yet a complete conviction that automatic de-crab is the way to go. Automatic roll-out is not considered essential with visually monitored automatic landings.

However, as a Phase III requirement a system has been tested. At the present time it is implemented with the beam error and the runway heading into the rudder; highly satisfactory control is maintained down to 60 knots even in the presence of cross-winds.

With improved means of path control and adequate failure warning and situation display systems, it is felt that the pilot is a very satisfactory monitor, and that no autopilot redundancy is required other than that for the pilot's information channel. The Category II system is deemed adequate for Category III operations without additional autopilot redundancy, provided that the "fail-passive" performance of the autopilot is assured and the pilot is given adequate failure warning and a separate approach display system.

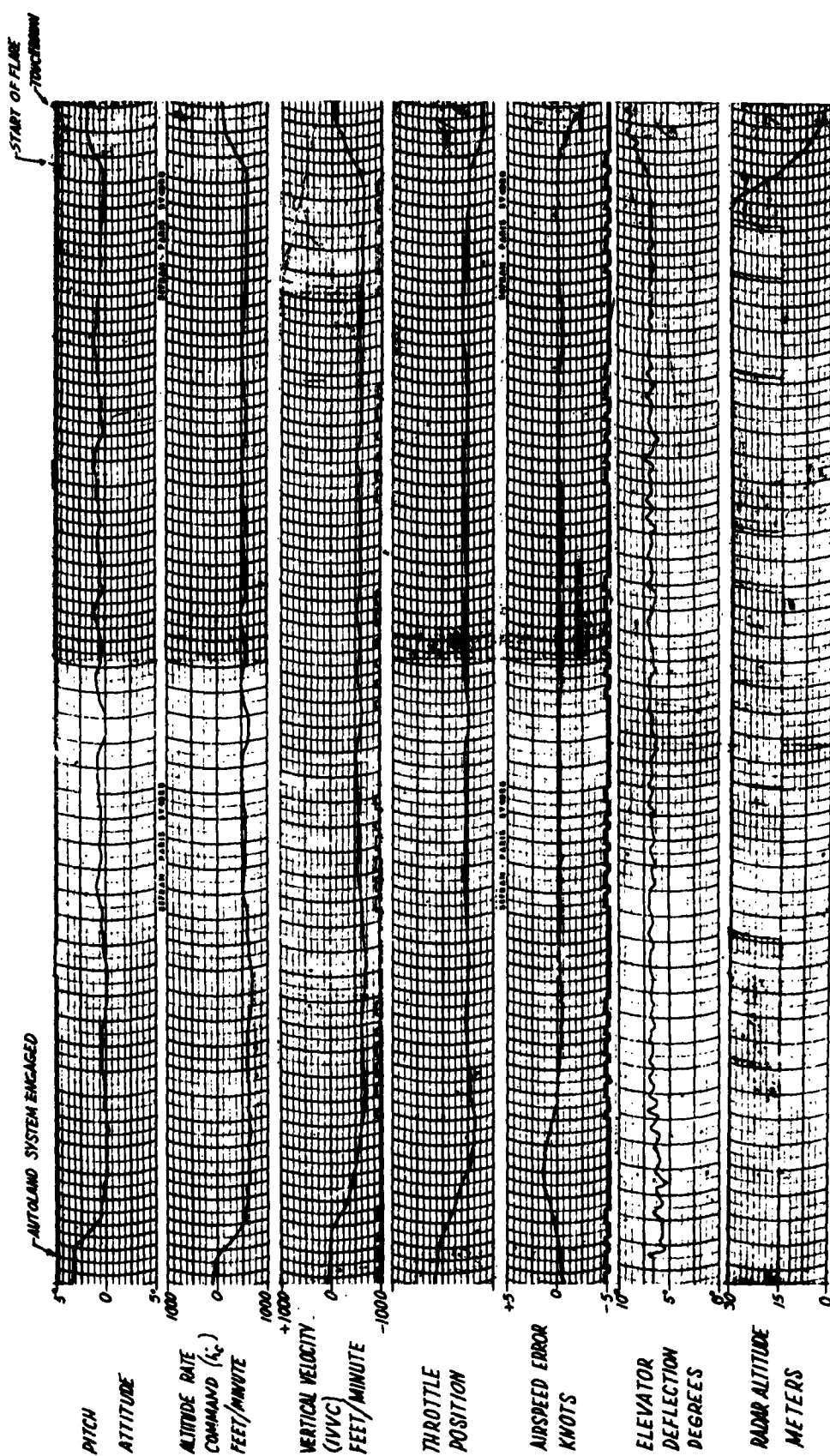


Figure 1. Airborne Recorder Charts of a Typical Automatic Landing - Caravelle

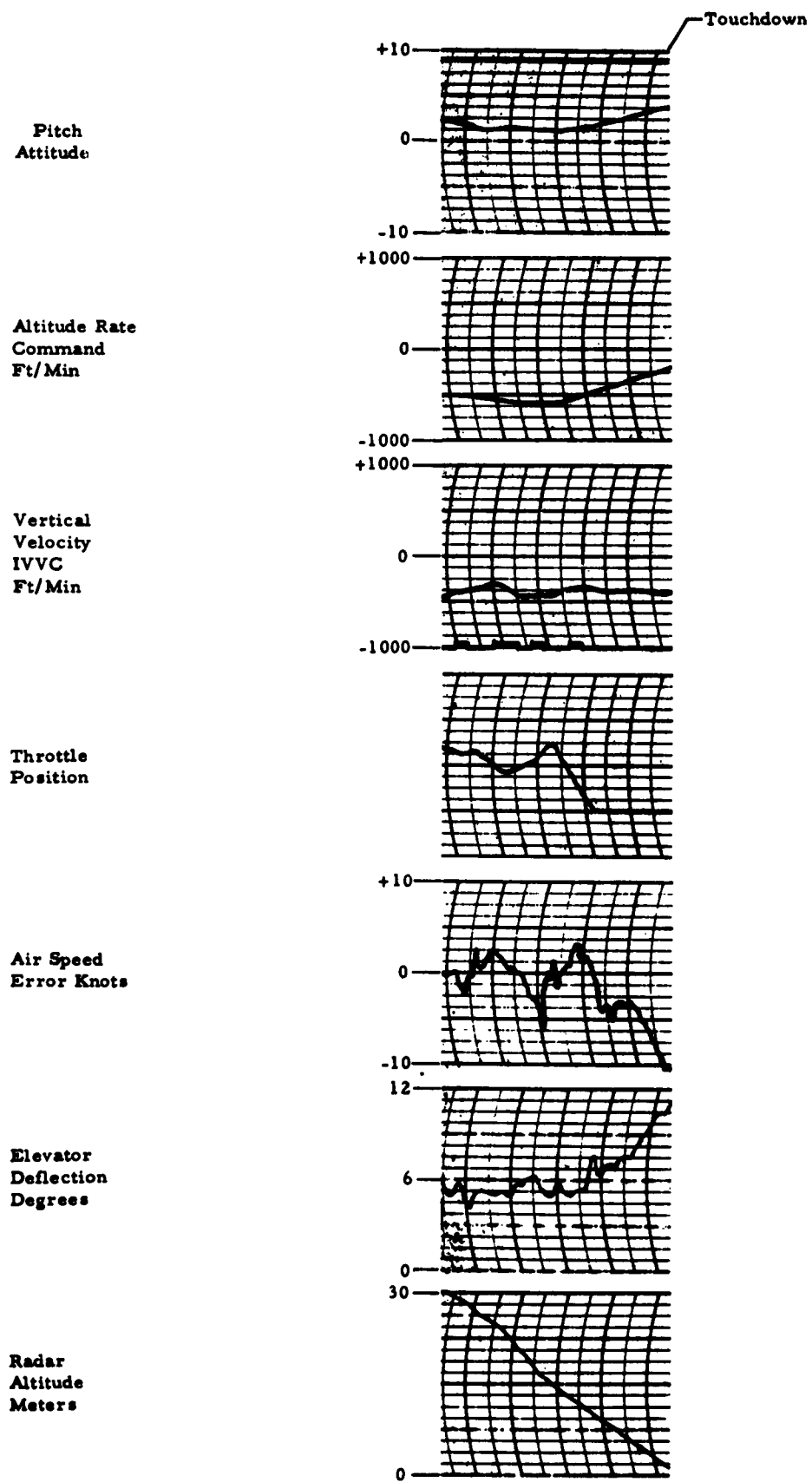
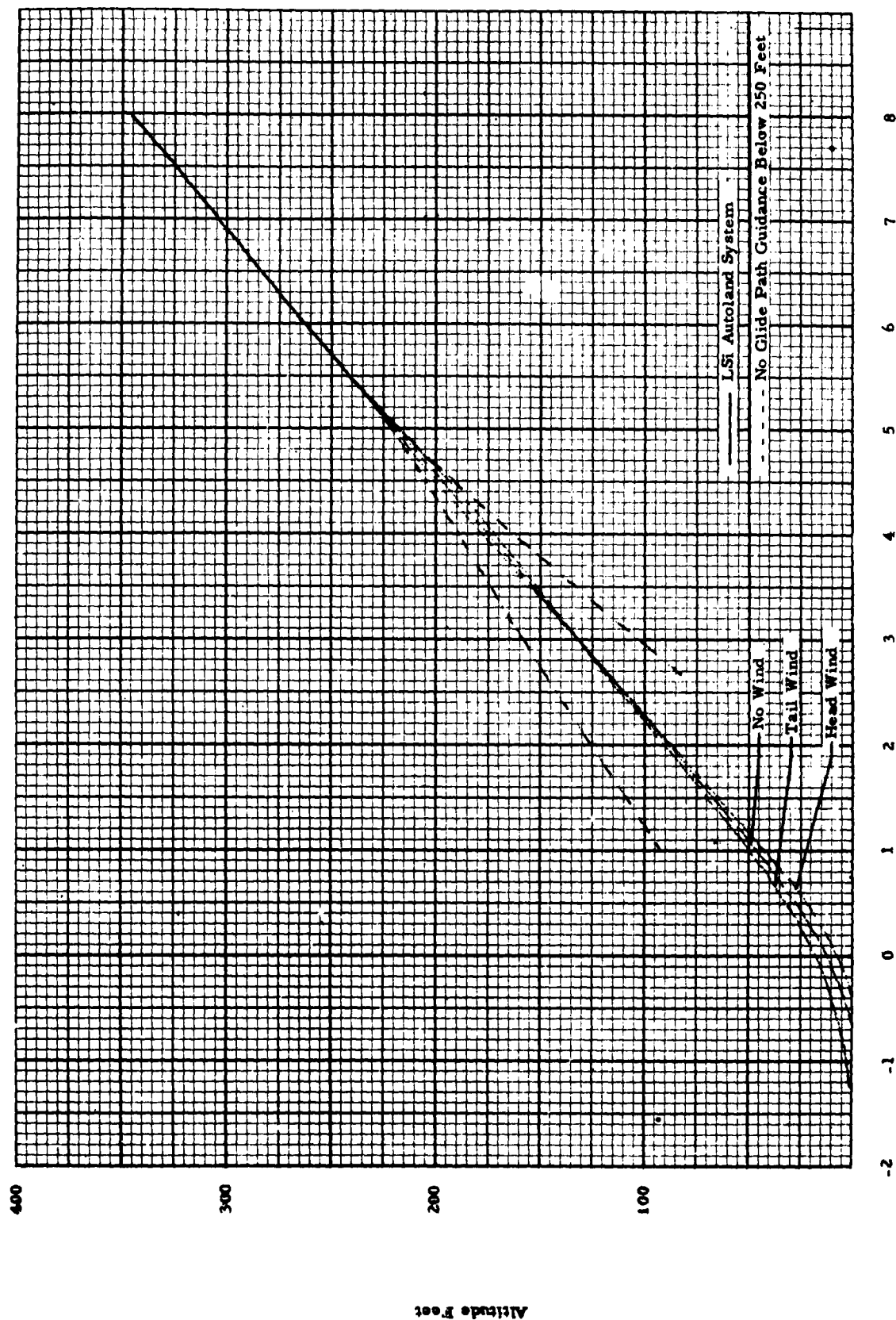


Figure 2. Airborne Recording Charts of an Automatic Landing with Severe Tail Wind Gust



Range From Glide Path Transmitter - 1000 Feet

Figure 3. Caravelle Automatic Landing with Horizontal Wind Shear
15 Knots/100 Feet Starting at 250 Feet

ELEVATOR POSITION

+ 4°

- 4°

+ 4°

ANGLE OF ATTACK

- 4°

80 FT

ALTITUDE

0

+ 4°

DIVISION OF CLEVITE CORPORATION

CLEVELAND, OHIO

PITCH ATTITUDE

0

- 4°

+ 20 FT/SEC

AIRSPEED

0

- 20 FT/SEC

0

ALTITUDE RATE

- 16 FT/SEC

0

ALTITUDE RATE
COMMAND

- 16 FT/SEC

Figure 4. Simulation Normal Automatic Landing - No Compensation

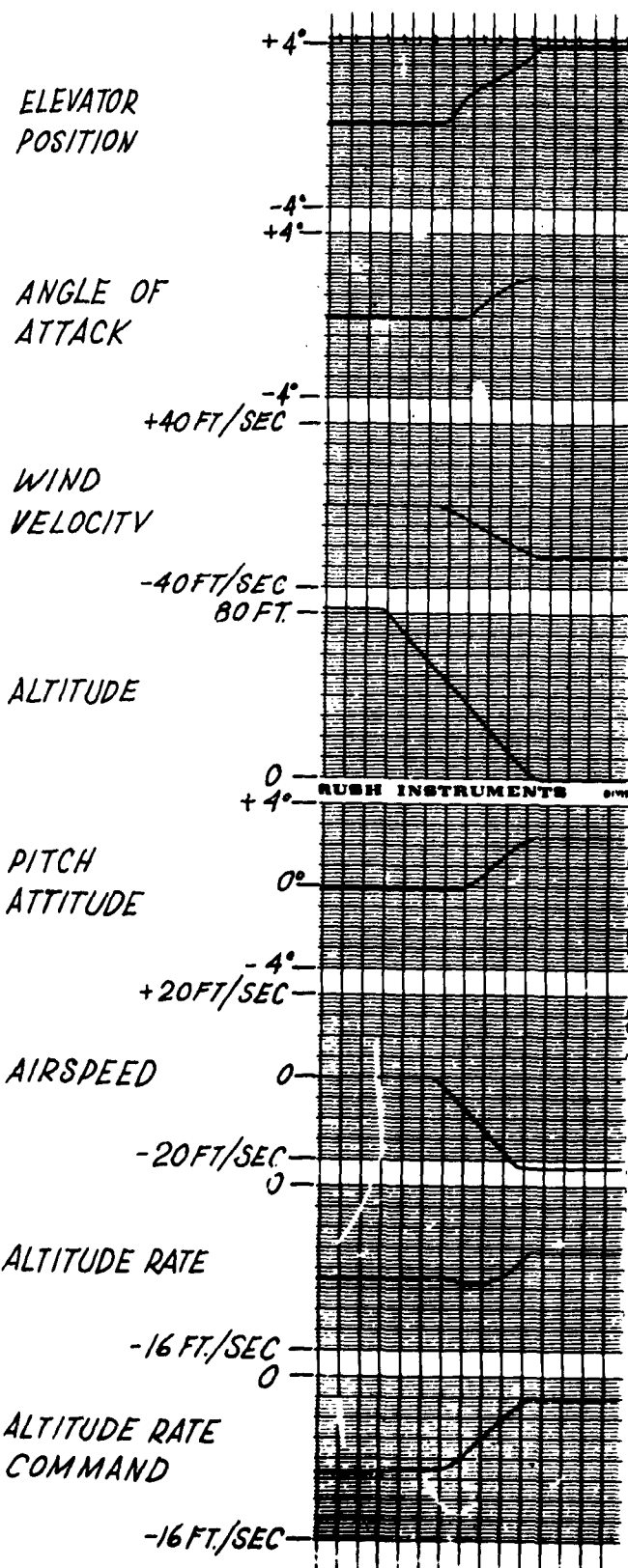


Figure 5 Simulation Caravelle Automatic Landing Tail Wind Gust with no Compensation

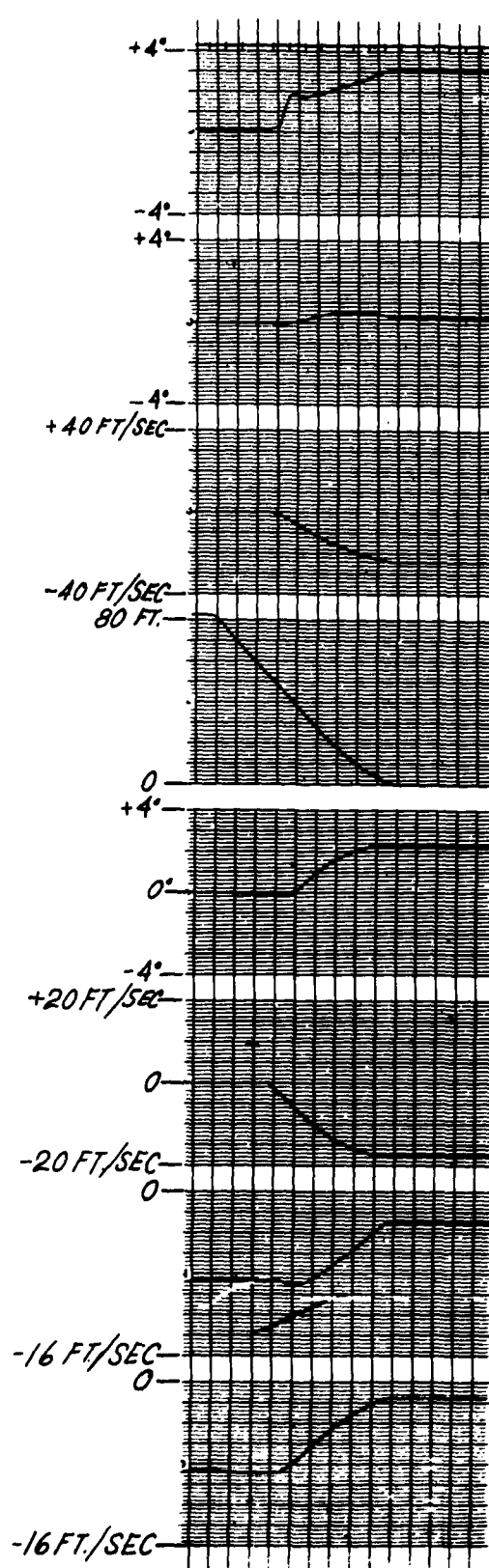


Figure 6. Caravelle Automatic Landing Tail Wind Gust with Compensation